MAKING MEANINGFUL CONNECTIONS WITH AUTOMATICALLY GENERATED, DYNAMIC, AND INTERACTIVE CONCEPT MAPS

A Dissertation

by

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Submitted to the Graduate and Professional School of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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December 2021

Major Subject: Curriculum and Instruction

ABSTRACT

In this four-article dissertation, I propose and examine the use of an educational technology, Dynamic and Interactive Mathematical Expressions (DIME) maps, to improve learning of physics. Receiving feedback from courses, conference and journal proposals, peers, and faculty helped me decide on methodological approaches for the articles in this dissertation. The coalescence of my professional and academic experiences guided my literature reviews and framed my interpretation of the various methodological analyses displayed in this dissertation. Each of the four articles have been published or submitted for publication in a journal prior to the defense of this dissertation.

Chapter one of this dissertation serves as an introduction, chapters two through five consist of the four journal articles, and in chapter six I reflect on the intellectual merit and broader impacts of this body of research. My intent with the first research article is to present a practitioner example of using DIME maps to teach physics. I also presented how DIME maps can fit together with the engineering design process and project-based learning to promote guided exploration of physics concepts. The second article focused on a randomized experimental study I conducted in 2018. In the second article, I used a multivariate analysis of variance and found that using DIME maps had a multivariate effect on the dependent variables: conceptual understanding and self-efficacy in physics. In the third article, which reported on a study conducted in 2019, I examined the correlations and determined that students who made greater use of the

DIME maps generally had higher growth in self-efficacy in physics. In the fourth study, I meta-analytically examined the data from 2018–2020 and concluded that using DIME maps has a positive effect on students' cognitive growth but not on affective growth, in terms of self-efficacy in physics. Further investigation is needed to examine whether differential effects would be experienced by specific populations or under differing conditions of implementation.

DEDICATION

To my eighth-grade science teacher, Mr. (John) Baron, for teaching me to believe in myself and to cherish science and mathematics.

ACKNOWLEDGEMENTS

I am grateful for my committee chair, Dr. Robert M. Capraro, and my committee members, Dr. Mary Margaret Capraro, Dr. Luciana R. Barroso, and Dr. Oi-Man Kwok, for their guidance and support throughout the process of putting together this dissertation. I appreciate the way they pushed me forward but also were compassionate and understanding when work and life became complicated by so many unexpected difficulties. I look to them as models of how I will soon support, advise, encourage, and mentor students. I hope to take all their best attributes with me and develop plenty of my own as I enter the next stage of my career.

My friend and colleague, DJ Beyette, has been indescribably supportive and helpful over the past four years. Without him, I literally could not have developed and continued this line of research. I am also grateful for the rest of the computer science and engineering team for their various contributions to this project. I hope we always find time to meet up for tacos as life becomes busy and our focus and energy are required elsewhere.

I want to thank Texas A&M University for being a phenomenal place to live and study; the College of Education and Human Development for broadening my network and involvement as I pursued my degree; and the people in the Department of Teaching, Learning and Culture for getting to know me personally and take an interest in my life. I run into administrators, advisors, faculty, and students who I have had limited interactions with, and they are consistently friendly, caring, and display genuine interest in my well-being.

Aggie STEM, the office, which gave me a place to work, play, and live throughout my PhD life. And Aggie STEM, the people. In particular, I would like to mention Aamir, Ali, André, Ashley, Caitlin, Cassidy, Chad, Choco, Danielle, Jessica, Jillian, Jonas, Jose, Julia, Katherine, Macie, Miriam, Mykala, McKennah, Noeline, Rachel, and Dr. Young for being my valued coworkers, competitors, mentors, mentees, and cherished friends since before I took my first class for this PhD. I extend a specific thank you to Jonas Chang and Mykala Madson, editors of Aggie STEM, who exhausted much of their time and effort in helping me improve my writing.

My friends. I have been fortunate to have made many friends through school, church, work, and life who have cared about me and been there for me at various times when I have needed it. You bring diversity, clarity, and purpose to my life. Thank you for being my friend.

Finally, and perhaps most importantly, as they are the ones who have been with me the longest and will forever be my family, I would like to thank my parents for loving and supporting me and letting me love and support them in return as time has marched on. My brother for understanding me in ways only a brother can and being there for me whenever I need him. My wife who stood by me through the hardest parts of this degree, and who, I know, will stand by me through the hardest parts of life.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Dr. Robert M. Capraro [chair] and Dr. Mary Margaret Capraro of the Department of Teaching, Learning and Culture, Dr. Luciana R. Barroso of the Department of Civil and Environmental Engineering, and Dr. Oi-Man Kwok of the Department of Educational Psychology.

The data for Chapters 2, 3, 4, and 5 were provided by Dr. Luciana Barroso of the Department of Civil and Environmental Engineering; Dr. Mary Margaret Capraro and Dr. Robert M. Capraro of the Department of Teaching, Learning and Culture; and Aggie STEM at Texas A&M University. Chapter 2 was published in 2021.

Donald J. Beyette, graduate student in the department of computer science and engineering, developed the educational technology, DIME maps, discussed in this dissertation. He also helped to write and edit Chapters 2 and 4.

All other work conducted for this dissertation was completed by the student, in collaboration with Dr. Robert M. Capraro and Dr. Mary Margaret Capraro of the Department of Teaching, Learning and Culture.

Funding Sources

Graduate study related to this dissertation was financially supported by the Graduate Merit Fellowship from Texas A&M University, by graduate assistantships from the Department of Teaching, Learning and Culture in the College of Education and

Human Development at Texas A&M University, and by Aggie STEM at Texas A&M University.

NOMENCLATURE

AI	Artificial intelligence
Aggie (noun)	A person who attends or once attended TAMU
Aggie (adjective)	Describing something as related to TAMU
APA	American Psychological Association
CATLM	The cognitive-affective theory of learning with media
CEHD	The College of Education and Human Development
DIME	Dynamic and Interactive Mathematical Expressions maps
MANOVA	Multivariate analysis of variance
NLP	Natural language processing
PBL	Project-based learning
PDF	Portable document format
STEM	Science, technology, engineering, and mathematics
TAMU	Texas A&M University
TLAC	The Department of Teaching, Learning and Culture
We	Hereafter refers to the authors of the individual journal articles

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1. INTRODUCTION

Textbooks are used ubiquitously throughout education and have evolved with advances in technology to meet the ever-growing needs of a digital-native generation of students. Textbooks are widely used in sciences, with many teachers even implementing reading quizzes to encourage students to diligently read their textbooks (French et al., 2015). While some students rarely touch their textbooks, most claim that they read their science textbooks sometimes or often (French et al., 2015; Podolefsky & Finkelstein, 2006). Students often turn to their textbooks as a trustworthy source of definitions, formulas, examples, and practice problems in mathematics (Weinberg et al., 2012) and engineering classes (Lee et al., 2013; Liberatore, 2017). Unfortunately, students often use their textbooks only for quick references, doing homework, or studying for exams and do not engage with the content for deeper understanding (Lee et al., 2013; Podolefsky & Finkelstein, 2006). Additionally, students often believe that the price of textbooks is unreasonably high (French et al., 2015; Martin et al., 2017; Skinner & Howes, 2013). Finally, from a research perspective, textbook copyright laws have impeded further reuse, revision, remixing, and redistributing of content by researchers, teachers, and students (Wiley et al., 2014). Thus, traditional textbooks have issues with cost, engagement, and copyright limitations.

The development of electronic textbooks has offered some solutions for these problems (Davidson & Carliner, 2014; Fowler et al., 2020; Rockinson-Szapkiw et al., 2013). Electronic textbooks are generally cheaper and offer additional opportunities for engagement with the content than their traditional, paper format counterparts. Students who use expensive textbooks read their textbooks about the same amount of time as students who use less expensive textbooks (French et al., 2015). Additionally, students who use electronic textbooks are more likely to use cognitive and self-regulation strategies (Rockinson-Szapkiw et al., 2013). Open textbooks are a subset of open educational resources and provide lower cost and more flexible copyright constraints (Clinton & Khan, 2019; Okamoto, 2013; Wiley et al., 2014). Through a meta-analysis of 22 studies consisting of 100,012 students, Clinton and Khan (2019) found "no differences in learning efficacy between open textbooks and commercial textbooks" (p. 1). In more recent studies, Fowler et al. (2020) and Clinton and Khan (2019) agreed that students who used open textbooks performed at least as well as students who used closed-source textbooks. Finally, open educational resources like open textbooks allow more freedom when it comes to creative use, as they are free from copyright restrictions (Wiley et al., 2014). Therefore, electronic textbooks, and open textbooks in particular, provide potential solutions to some of the issues associated with traditional textbooks.

Since the inception of electronic and open textbooks, calls for further improvements that complement and enhance students' textbook-based learning have been made. For example, technology should be implemented to assist in the navigation of these textbooks as a way to improve students' desire to engage with electronic resources (Woody et al., 2010). Visualization techniques could also be used to support finding relevant learning material and developing a deeper understanding of the content (Klerkx et al., 2014). In response to these calls, several authors have begun producing interactive textbooks (see Fowler et al., 2020; Liberatore, 2017; O'Bannon et al., 2017), allowing for further engagement with the textbook knowledge. Interactive concept maps have also been explored with some success. However, these technologies take significant time and effort from the curriculum designers. Therefore, the educational technology known as the Dynamic and Interactive Mathematical Expressions (DIME) Map system was developed to automatically generate dynamic and interactive concept maps from electronic textbooks.

1.1. Purpose of the Dissertation

The purpose of this four-article dissertation was to examine the effects of using DIME maps on students' learning and self-efficacy. First, I illustrate how DIME maps and the engineering design process work together in an example five-day activity. Then, I explore how using DIME maps compared to traditional group learning using data collected in the summer of 2018. For the third article, I used data from a follow-up study conducted in the summer of 2019. In 2020, I replicated the study in a unique setting, a virtual summer camp during the COVID-19 pandemic. Finally, I compiled the results from three years of the implementation of DIME maps in the fourth article. I believe that the results from these four articles provide insight into the effectiveness of DIME maps as well as considerations for implementation in various settings. The knowledge gained from these articles can guide the development of DIME maps and provide benchmarks for future studies on similar educational technology. Therefore, the findings from this dissertation provide valuable insights on an educational technology that can address the issues associated with widespread use of textbooks and the rising generation's reliance on technology.

1.2. Research Questions

The following research questions guided the development of my four-article dissertation:

1. How can DIME maps be integrated into a STEM PBL activity in a way that assists students engaging in the engineering design process?
2. What features of DIME maps help students understand core concepts in physics?
3. Is there a multivariate relationship or pattern between using DIME maps and two learning outcomes for students: self-efficacy towards learning physics and understanding connections between content knowledge?
4. How do students feel about using DIME maps—what aspects of DIME maps do students consider helpful or harmful to their learning process?
5. What is the relationship between students' interactions with DIME maps and students' self-efficacy towards physics?
6. What effect has using DIME maps had on cognitive and affective learning outcomes for students?

1.3. Literature Review

Traditionally, textbooks contain knowledge linearly, with one large section of expository text after another. When new information is presented linearly, cognitive dissonance (Brehm & Cohen, 1962; Festinger, 1962) and cognitive load (Sweller, 1988) can combine to create an insurmountable barrier to assimilation. According to educators and cognitive psychologists, a linear representation of knowledge is contradictory to the internal representation of knowledge in our minds (Kalyuga, 2006), which is better represented as a web of interconnected ideas with organization and structure (Hiebert & Carpenter, 1992; Saxe et al., 2013; Stelzer et al., 2009; Sweller, 1988). In schools, students have often turned to rote learning in an attempt to quickly remember facts and information from these large sections of text for summative tests without seeking further understanding.

Rote learning is a short-term solution, because students attempt to memorize mathematical formulas and ideas as independent and distinct pieces of information. Unfortunately, rote learning alone has been considered to be ineffective for long-term retention (Byers & Erlwanger, 1985; Cai & Wang, 2010). Instead, the assimilation theory of meaningful learning states that meaningful learning is best achieved by anchoring new knowledge in prior knowledge (Ausubel, 1968). This is the theory that led Ausubel to famously state, “If I had to reduce all of educational psychology to just one principle, I would say this: The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly” (Ausubel, 1968, epigraph). If students are enabled to integrate new concepts and prepositions with their existing knowledge, meaningful learning can occur (Novak, 1998). However, many students struggle with achieving meaningful learning when reading traditional textbooks, as the connections between concepts, equations, expressions, and formulas are hidden due to the author-centric linear representation of knowledge. Although linear representations of knowledge in textbooks are not inherently bad for student learning, dynamic and adaptive non-linear transformations of knowledge facilitate learning for broader populations, as the human mind requires new and prior knowledge to be linked together in a complex neural network. When students rely only on memorization, information is typically stored as disparate pieces of knowledge in long-term memory. Memorization makes it difficult to draw connections between information and develop conceptual understanding (Bransford et al., 1999). Thus memorization is not an effective strategy for meaningful learning.

Concept maps and other graphic organizers have been suggested to improve meaningful learning for students. Graphic organizers enable students to visualize connections between prior knowledge and new learning (Hill, 2005; Lopez et al., 2013; Novak, 1998). By demonstrating the connections between concepts, concept maps reduce the cognitive load required to process new knowledge (Hill, 2005; Novak, 1998; Stull & Mayer, 2007). This process allows concept maps to be invaluable tools in all levels of learning. Through multiple systematic reviews, it has been found that concept mapping, whether studying or constructing concept maps, has potential for learning gains (Adesope & Nesbit, 2010; Hartmeyer et al., 2018; Horton et al., 1993; Mihai et al., 2017; Nesbit & Adesope, 2006; Novak, 1990; Schroeder et al., 2018; Yue et al., 2017). Developed from research on concept maps, DIME maps have the potential to improve learning with the added benefits of being automatically generated and highly interactive. The purpose of my research resulting in the proposed articles is to evaluate the effectiveness of using DIME maps to improve learning outcomes.

1.4. Methodologies

The different quantitative methods utilized in the four articles were chosen based on the research questions for each study and the expertise of the supporting committee. In the first article, we reflected on an example of using DIME maps in classroom action research. A focus group was interviewed to examine the multiple features of DIME maps that helped them to better understand core concepts. For the second article, we used MANOVA to determine the effect of using DIME maps on students' learning with respect to two aspects or dependent variables, self-efficacy in learning physics and understanding of concepts. The third article concerned user interactions, and so we primarily focused on the correlations between the number of interactions students had with the DIME map and their resulting growth in self-efficacy in physics. In the fourth article, meta-analytic methods specifically designed for a small number of studies was used to examine the overall effect that DIME maps had on self-efficacy and cognitive growth in physics. In general, Hedges' bias-corrected effect sizes (g) were computed and reported to compare with prior literature and allow for future work to engage in ongoing meta-analytical thinking and combination.

1.5. Results

We used the results throughout this dissertation to answer the many research questions we posed before each study was conducted. In the first article, we presented how DIME maps can be integrated into a STEM PBL activity through an illustrative example. In that example, students used DIME maps in the ideate and analyze ideas phases of the engineering design process. Students appreciated how they could use their

DIME map as an interactive map that allowed them to navigate the PDF textbook chapter. Students also enjoyed being able to manipulate and rearrange the DIME map and focus on key concepts. Finally, students in the focus group remarked how the visual representation of concepts and relationships between concepts was valuable.

We found a multivariate relationship in the second study, indicating that using DIME maps had a positive effect on self-efficacy toward learning physics and understanding of connections between content knowledge. While no statistically significant interaction effect was found for gender, it is worth noting that female students using DIME maps outperformed male students, while the opposite was true for the control group. In the qualitative portion of this study, we found that students appreciated the high level of interactivity (specifically mentioning clicking, navigating, and searching) and that the DIME maps visually represented concepts and relationships between concepts. These findings were similar to those in the first study. Additionally, the students in the second study commented on how DIME maps served as a tool for empowering their learning and making learning more accessible. One negative trait of DIME maps was revealed in this study; students encountering DIME maps for the first time thought they looked complex with too many concepts and connections presented at once without a prespecified structure. We considered whether students who were less confused or who persisted through the initial complexity would gain more from using DIME maps. For this reason, in the third article, we explored the interactive nature of DIME maps and found that students who interacted more with their DIME maps gained more in terms of self-efficacy in physics. Looking at specific interactions, we found that the most used functions were clicking/dragging, followed by searching. Thus, we found evidence that students did utilize the features mentioned in the previous study.

Finally, we performed a meta-analytical combination of three years of data in the fourth article. Across three studies including over seventy students, we found DIME maps to have a statistically significant positive effect on cognitive outcomes and a positive, but not statistically significant, effect on affective outcomes. Implications and discussions of all findings are presented within each respective chapter.

1.6. Journal Selection

I have created a collection of potential journals to submit the four articles of my dissertation. Each potential journal outlet has been vetted for appropriateness for each proposed dissertation article along with supporting documentation. First, a list of education journals was obtained from Scopus. The list was filtered for journals focused on educational technology or general STEM education. The journals were then ranked by Scimago Journal Rank (SJR) and Source Normalized Impact per Paper (SNIP). Only journals with high SJR and SNIP were considered. I further filtered the list down to only journals that focused on educational technology, online/remote learning, and/or STEM education. Alignment with each journal's scope and aim was also considered. The editors of the journals are top scholars in their related fields. The journal quality metrics and other relevant information for determining appropriateness were gathered using the journals' websites, Scopus, Scimago Journal and Country Rank, and Cabell's Directory of Publishing Opportunities. For a list of potential journals for each proposed article as well as related notes on each journal, see Table 1.1. These journals were carefully selected as top-quality outlets for the proposed articles. Article 1 has already been published at the time of this dissertation, and so only the appropriate citation is displayed.

Table 1.1

Articles and Proposed Journals

	Proposed Journal #1	Proposed Journal #2
Article 1: Using DIME maps and STEM project-based learning to teach physics	Published. The full citation for this article is: Rugh, M. S., Beyette, D. J., Capraro, M. M., & Capraro, R. M. (2021). Using DIME maps and STEM project-based learning to teach physics. *Interactive Technology and Smart Education*. Advance online publication. https://doi.org/10.1108/ITSE-07-2020-0109	
Article 2: A first look at effectiveness: DIME maps—The evolution of concept maps	*Journal of Research on Technology in Education*	*Australasian Journal of Educational Technology*
SNIP / SJR	1.241 / 0.74	1.95 / 1.397
Editor-in-Chief	Albert Ritzhaupt	Linda Corrin et al.
Publisher	Taylor and Francis	Australasian Society for Computers in Learning in Tertiary Education
Article 3: Improving self-efficacy with computer-generated concept maps: Analysis of user interactions	*Journal of Computer Assisted Learning*	*Online Learning Journal*
SNIP / SJR	2.212 / 1.583	1.981 / 1.182
Editor-in-Chief	Paul A. Kirschner	Peter Shea
Publisher	Wiley-Blackwell	The Online Learning Consortium
Article 4: Breaking barriers for STEM learning: A meta-analysis of three years of findings on DIME maps	*Educational Technology and Society*	*Journal of Engineering Education*
SNIP / SJR	2.036 / 1.448	6.264 / 3.896
Editor-in-Chief	Maiga Chang et al.	Lisa C. Benson
Publisher	Educational Technology and Society	Wiley Online Library

Note. SJR: SCImago Journal Rank in 2020; SNIP: Source Normalized Impact per Paper in 2020. All journals included followed a double-blind peer review process.

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2. USING DIME MAPS AND STEM PROJECT-BASED LEARNING TO TEACH PHYSICS*

The engineering process is critical for the innovation of solutions to everyday problems, which grow increasingly complex in the modern world. As such, few would argue against the fact that the need for engineers today is greater than any time in our nation's past. The training of engineers begins in primary education, and one method of instruction that aims to adequately prepare students for advanced engineering learning is engineering design. The National Research Council (2012) defined engineering design as “the iterative cycle of design that offers the greatest potential for applying science knowledge in the classroom and engaging in engineering practices” (pp. 201–2) Core principles of engineering design models include defining and determining constraints of engineering problems, designing solutions to those problems, and selecting an optimum solution (Next Generation Science Standards, 2013). Furthermore, by exposing pre-college students to engineering activities, we can spark interest in science, technology, engineering, and mathematics (STEM), which can significantly influence future career plans (National Science Board, 2010). These core principles and the effects of early exposure to engineering position engineering design as an ideal process for students to learn and engage with in order to be better prepared to solve the problems of a

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 Chapter 2 in this dissertation is adapted from the Author Accepted Manuscript version of Rugh, M. S., Beyette, D. J., Capraro, M. M., & Capraro, R. M. (2021). Using DIME maps and STEM project-based learning to teach physics. *Interactive Technology and Smart Education*. Advance online publication. https://doi.org/10.1108/ITSE-07-2020-0109 technologically advanced world. Teachers can engage students in the engineering design process through STEM project-based learning (PBL).

Although many versions of PBL have been explored, we follow the definition of STEM PBL given by Capraro and Slough (2013): "an ill-defined task within a well-defined outcome situated with a contextually rich task requiring students to solve several problems which when considered in their entirety showcase student mastery of several concepts of various STEM subjects" (p. 2). Importantly, STEM PBL can incorporate engineering design principles into K–12 learning (Morgan et al., 2013). Furthermore, PBL allows for students to make connections between the content they are learning and practical, real-world experiences and applications.

Developing an intervention—one that a) builds on prior research, b) addresses the needs of individual students, and c) bridges new learning with old—may make learning more accessible in physics courses. Recent studies attempting to address these criteria have discussed the use of interactive digital textbooks to improve learning (e.g., Bikowski & Casal, 2018; Choi & Lam, 2018; Liberatore et al., 2020). However, interactive digital textbooks generally have required a significant contribution of time and effort to create. Our proof-of-concept model builds on the idea of an interactive textbook intervention, but our study additionally incorporates the well-known and well-articulated learning strategy of using concept mapping, a synthesis made possible through developments in artificial intelligence. Therefore, we created Dynamic and Interactive Mathematical Expressions (DIME) maps, which are automatically computer-generated, interactive concept maps. Eventually, with DIME maps, textbooks based on content with mathematical formulas can be transformed automatically by artificial intelligence into interactive digital textbooks. The purpose for this article is to present an example of how DIME maps were used to promote active learning and engagement in the engineering design process within a STEM PBL activity for middle and high school students.

2.1. Historical Background

As the study of teaching and learning has developed, information has become more dense, subjects have developed along different lines, those disparate subjects have evolved their own language, and concepts and word definitions once shared by the larger field have become more specific to nuances in individual and specialized disciplines and are therefore far removed from everyday use and understanding (Kwok et al., 2020; Rugh et al., 2018). This evolution of various subjects within the same field dramatically increases the cognitive load for those who are new to the discipline. However, although the language used to teach specific content has become more complex, the language of mathematics has remained relatively stable, supporting and demonstrating the relationships between most scientific concepts that a student might encounter.

At one time, methods for teaching and learning science, engineering, and mathematics were simpler; in mathematics, for example, a student learned from a mentor at the university. In this apprenticeship model, the young mathematician was finished when the mentor deemed it so (Boyer & Merzbach, 2011; Cajori, 1999). Their successful completion of a degree was not based on a set of courses to be taken or some idea of a test. It was not until 1817 that engineering left the apprenticeship model and colleges of engineering and formal engineering courses began to replace the apprentice-master model (Borrego, 2007; Seely, 2005). As the field evolved, the learning curve accelerated exponentially as it became informed by advances in closely related subjects, and it continues to do so today. The loss of the close, personal instruction of the apprenticeship model and the adoption of the mass, regimented instruction that replaced it hindered academic success and concept comprehension for many students, not only in engineering, but in education more generally throughout the 20th century. Teaching and learning researchers sought to address this with a resurgence of emphasis on student-centered learning approaches and theories.

2.2. Underlying Theories of Learning

Two categories of theories of teaching and learning were essential for the development of our approach in this study: constructivism and cognitivism. The two main foci of this paper, STEM PBL and the educational technology, were developed, implemented, and interpreted with these two underlying theories of learning.

In particular, constructivist learning theories guided the development of the STEM PBL activity. Project-based learning has developed from the project method of teaching by Kilpatrick (1918) and Dewey (1938). From a constructivist perspective, students engaging in STEM PBL are active investigators of their learning. Primarily used in the K–12 setting, STEM PBL is founded on constructivist practices such as engaging students in collaborative problem solving and hands-on/real-world learning experiences with an added focus on interdisciplinary STEM learning (Capraro & Slough, 2013; Clark & Ernst, 2007). This focus on student-centered learning allows STEM PBL to engage students in more meaningful learning where new knowledge is anchored in real-world experiences and applications of knowledge.

Within the lens of constructivism, the assimilation theory of meaningful learning (Ausubel, 1968) aided in the development and understanding of the benefits of using the educational technology in this study. The assimilation theory of learning, which claims that students relate new knowledge into the context of existing knowledge structures (Mayer, 1979), has been used to explain the learning gains that concept maps offer (Novak, 1990; Novak & Cañas, 2007; Novak & Musonda, 1991). As with advance organizers before them, concept maps allowed the knowledge giver (expert) to construct a visualization or organization of knowledge for the knowledge receiver (learner or novice) to understand how the expert organized and interpreted the material. The advantage was that this lowered the cognitive demand of learning, but, unfortunately, knowledge presented by the concept map was only accessible to those learners with the prior knowledge necessary to make use of it (Novak, 1990). As the field of teaching and learning works to democratize the classroom space, single views or entitled perspectives, as what is often presented by concept maps, no longer meet the needs of most learners (Moschkovich, 2013). In this increasingly digital era, there is a need to link learning theories (e.g., constructivism and cognitivism theories underlying concept maps) through artificial intelligence technology to provide students with automatically generated interactive concept maps to help navigate the textbook and to assist in learning in social settings. The next few sections contain further descriptions of the educational technology and engineering design nested in STEM PBL that were used in this study; connections to theories and prior research on students' learning are also presented.

2.3. Introducing Dynamic and Interactive Mathematical Expressions (DIME) Maps

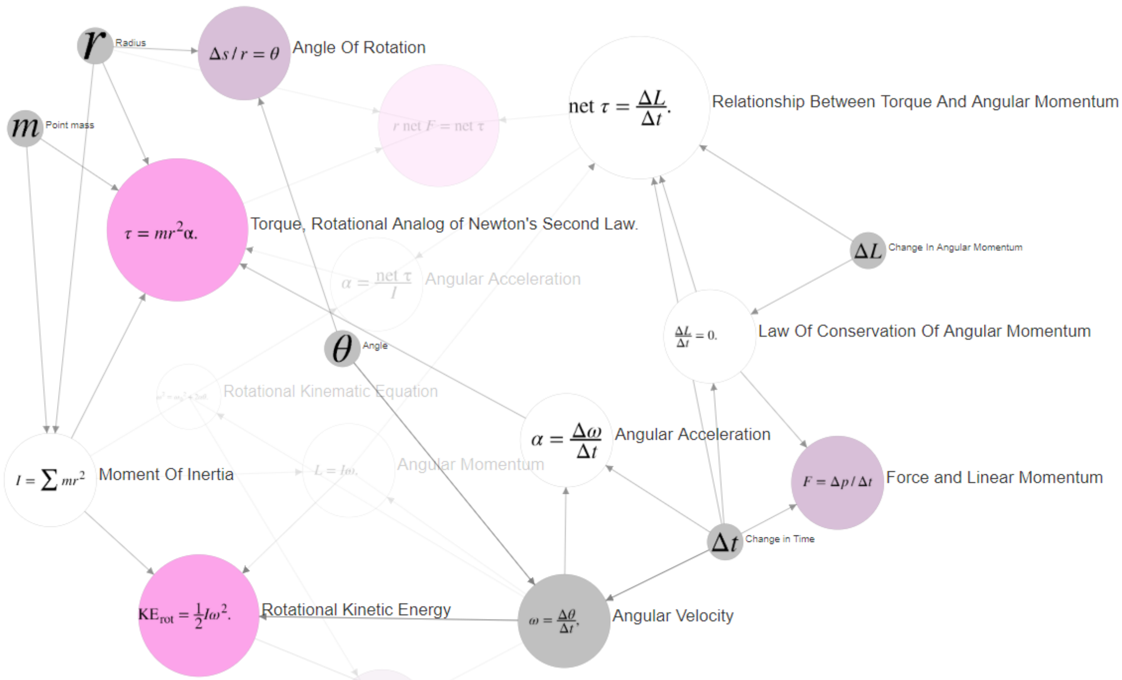
We created the DIME Map system as a meta-cognitive tool to organize and support personalized learning inside and outside the classroom setting. This learning technology can assist students in self-guided study and exploration of concepts in textbooks. The DIME Map system creates DIME maps, which are automatically generated from portable document format (PDF) documents containing mathematical objects (i.e., equations, expressions, and variables) by reconstructing the connections between each mathematical object into an interactive concept map. (Beyette et al., 2019; Rugh et al., 2019). The user, generally a teacher or researcher, begins by uploading a PDF file of a desired textbook chapter to the DIME Map system, a machine-learning program that employs artificial intelligence to identify and define mathematical objects. The identified mathematical objects are connected automatically based on a set of logic rules, and the resulting map is displayed to users as a dynamic and interactive concept map (see Figure 1) next to the original PDF document.

Automatically transforming mathematical knowledge from physics textbooks into dynamic concepts maps allows students to be exposed to multiple visual representations and organizations of knowledge. This knowledge is automatically transformed from the text into interactive concept maps by extracting and linking mathematical concepts with heuristic rules and artificial intelligence, allowing the user to personalize their own DIME map. Choi and Lam (2018) suggested that making technology personalizable for different learners is one of the main goals for the future of interactive textbooks, and DIME maps fill this role with ease. Figure 1 shows an example of a DIME map that represents the essential mathematical concepts and relationships contained in one chapter of a physics textbook. Figure 6 shows an example of a DIME map that was created in class and rearranged by a student to fit their personal conceptual understanding of the material.

DIME map links (or arrows) represent the relationships between mathematical objects and are understood by the rule “build(s) into.” This rule is used to iterate through mathematical expression objects (e.g., stand-alone expressions or expressions on the right-hand side of an equation), linking any expressions that are used in the formulation of an equation (i.e., object → equation). These links can be thought of as connections that help build the student’s conceptual understanding, which is required for them to correctly apply and understand procedure skills (see Capraro & Joffrion, 2006). The “build(s) into” relationship can be thought of as a selected rule for how the mathematical objects should be connected together. This rule can be replaced with any arbitrary rule that establishes a well-defined relationship between two mathematical objects. Because the meaning is well defined, students can better understand the connections between concepts and mathematical semantics, syntax, and meaning, an understanding that is claimed to be critical for students (Capraro et al., 2010). The direct connections to the text as well as the well-defined relationships between mathematical objects in DIME maps enable students to build a more well-rounded mathematical vocabulary and understanding of these relationships.

Figure 2.1

Example of a DIME Map



Manually drawing maps such as the one shown in Figure 2.1 for every chapter and textbook a teacher uses would not be feasible for teachers or students, as manually creating concept maps is labor intensive and requires an expert-level understanding of the relationships between concepts. In addition, resulting concept maps would be static, not allowing the student to easily interact, personalize, or share the concept map. However, with DIME maps, the mathematical knowledge in PDF textbooks is extracted to create an interactive and malleable concept map. Students are able to navigate between the DIME map and traditional textbooks by clicking on a mathematical object, which takes them to the first derivation of the selected concept. Double clicking brings up a window that searches Google for additional definitions (for a similar application of this feature, see Leake et al., 2004). Students can also search for concepts in the map, allowing them to easily follow along with lectures or questions. Lastly, mathematical objects (nodes) in the map can be hidden or removed to reduce cognitive load as well as be rearranged into any orientation, allowing the student to create a configuration that is most effective for their own concept understanding and retention. With their potential to engage students in mapping and visualizing their own learning while also making textbook information digestible and personalizable, DIME maps are a powerful tool of instruction that assists teachers in democratizing learning in their classroom.

2.4. Model for the Engineering Design Process

Models for engineering design vary widely. Some models consist of as few as three steps whereas others may contain more than ten steps (Capraro & Slough, 2013; Cross, 2000; Dym & Little, 2009; Morgan et al., 2013). The choice of a model can depend on a variety of considerations, such as intended purpose, quality control, economic use of resources, elegance, or applicability (Capraro & Slough, 2013). It is a good idea to choose and follow a specific engineering design model in order to guide implementation during an engineering design activity.

For the STEM PBL activity described in this paper, we chose to follow the engineering design model used by Morgan et al. (2013). This model, depicted in Figure 2.2, consists of seven steps: identify problems and constraints, research, ideate, analyze ideas, build, test and refine, and communicate and reflect.

Figure 2.2

The Seven-Step Engineering Design Model Chosen for this Study

Note. Adapted with permission from Morgan et al. (2013)

In the identify problems and constraints phase, engineers fully establish the goal of the process. Engineers must fully consider the requirements of the consumer, the demands of society, or the statement of a problem. Additionally, engineers explore and identify potential constraints and criteria. Constraints include limitations such as time and resources. Criteria include desirable or required aspects of the final product.

In the research phase, engineers look into the background information that could help formulate and analyze potential solutions. It is here that environmental concerns, scientific properties of the materials involved, and additional laws or standards should be fully investigated. Any applicable mathematical formulas and scientific concepts must also be understood in order to create feasible design options.

In the ideate phase, engineers employ divergent thinking to brainstorm reasonable solutions to the established problem. Engaging in STEM PBL activities involving engineering design principles has been shown to improve students' attitudes about divergent thinking and the importance of new and alternative ideas (Bicer et al., 2019). The ideate phase is critical to the engineering design process because it can lead to multiple creative and innovative solutions.

In the analyze ideas phase, engineers explore the created design ideas and select the optimal solution. Optimization, or identifying the best design for a given task, is critical to this phase of this engineering design model. Optimization before building has replaced numerous rounds of trial-and-error, leading to more efficient use of resources, such as time and materials, necessary to upgrade and replace multiple prototypes (Kelley, 2010). During this phase, engineers consider relevant constraints, criteria, formulas, and concepts identified in the research phase. Only then can the best design be chosen to proceed with building.

In the build phase, engineers construct the chosen design. They contact suppliers, gather materials, and finalize assembly processes to create a working model that can be tested.

In the test and refine phase, the prototype is experimentally evaluated, tested under working conditions, and improved. Predictions, observations, and analyses should be recorded in order to inform refining the design into the final product. By this phase, catastrophic failure should only be the result of a major error in a previous phase. If the prototype is completely unacceptable, a critical analysis should be conducted as the engineer returns to the ideate or analyze phases to pose an alternative solution. The final model should fit all design considerations, constraints, and goals established in the identify problems and constraints phase.

In the communicate and reflect phase, engineers share the results with stakeholders in the problem. Effective communication skills are required to meet market demands and the demands of the consumer as well as acquire approval and funding for projects. Results should also be shared and stored in the form of written documentation. Engineers in this phase also reflect upon their designs and make notes for future iterations, related projects, and to inform the client of any last concerns.

2.5. The STEM PBL and Engineering Design Activity

The activity described in this paper involves integrating the use of DIME maps in STEM PBL. STEM PBL is built on a foundation of engineering design principles and integrates into K–16 formal and informal learning experiences through implementing well-defined outcomes and ill-defined tasks (Capraro & Slough, 2013; Cross, 2000; Han et al., 2015). A well-defined outcome in STEM PBL involves explicitly telling students what the problem is, what criteria the final product should meet, and what constraints are placed on potential solutions or designs. Such a well-defined outcome is crucial to the engineering design process and STEM PBL (Capraro &Slough, 2013; Daugherty, 2012). An ill-defined task, in turn, requires that students not be told instructions or clear guidelines for how to achieve the desired outcome. By not restricting students to specific courses of action or designs, STEM PBL allows for creativity and divergent thinking to flourish (Bicer et al., 2019). Through STEM PBL, students engage in the engineering design process (Morgan et al., 2013), which provides multiple benefits:

- cultivates 21st century skills, such as problem-solving and creativity (Bicer et al., 2019; Morgan et al., 2013),
- leads to efficient solutions (Morgan et al., 2013),
- provides realistic contexts for the application of math and science (Daugherty, 2012; Morgan et al., 2013),
- develops stronger interest in STEM (Bicer & Lee, 2019; Morgan et al., 2013)
- increases social awareness (Akleman et al., 2019)

Although the theoretical framework for this study can be understood as the product of constructivist and cognitivist learning theories, a subtle interplay is located in the connections that students make. Students engaged in STEM PBL activities are making connections between new learning and real-world experiences. On the other hand, students using concept maps, and DIME maps in particular, are making connections between new learning and prior knowledge. Together, both STEM PBL and DIME maps provide contexts for making connections between interdisciplinary knowledge and their constructed body of knowledge and experience. With high strengths of association, new learning is firmly anchored in prior knowledge, past experiences, and real-world application, making DIME maps a powerful tool to promote meaningful learning in the context of STEM PBL.

2.6. Methods

The first author was a physics teacher engaging in classroom action research, the primary research method guiding this study. In classroom action research, the teacher focuses attention on a problem or question about their own teaching practice (Denzin & Lincoln, 2000; Mettetal, 2002). The teacher/researcher team also conducted semi-structured interviews with students selected for their level of participation and engagement with DIME maps and the STEM PBL activity. Thus, the teacher utilized classroom action research and the semi-structured interviews to improve teaching practice and answer the following research questions:

1. How can DIME maps be integrated into a STEM PBL activity in a way that assists students engaging in the engineering design process?
2. What features of DIME maps help students understand core concepts in physics?

To answer these questions, the teacher and researchers worked together to make naturalistic observations in the setting described below (see Lincoln & Guba, 1985). Each took notes on the order of teaching and how students engaged in the activity. The team met together between classes to discuss ways to improve implementation in further iterations. This iterative process was carried out over three years (2018–2020) of STEM summer camps in which the teacher taught a course on rotational motion.

In the following sections, we present a compilation of reflections and notes from multiple researchers as a day-by-day analysis of the STEM PBL activity and how we used DIME maps to teach physics. The teacher and researchers reviewed these sections to ensure fidelity to their individual perceptions of events and of students' engagement in learning. Following the day-by-day analysis, an evaluation of DIME maps and the STEM PBL activity is presented through quotes from the semi-structured interviews and reflections by the teacher/researcher team.

2.7. Setting/Context

The Aggie STEM summer camp is designed to provide a fully immersive STEM experience for students who are particularly interested (or sometimes whose parents are interested for them) in STEM careers. The camps serve 6th–12th grade students, but there are occasionally special camps for elementary students and professional development "boot camps" for in-service teachers, which are also STEM-oriented. Furthermore, different camps have different focuses (e.g., health sciences, engineering, or computer science), and each individual camp includes unique learning experiences (e.g., a mathematical sciences camp may include physics, laboratory sciences, and aerospace courses or activities). Students attending the camp engage in STEM PBL-based classes, interact with STEM professionals, tour science and engineering labs, and receive specialized SAT/ACT training. The STEM PBL activity described in this paper comprised the students' physics class for three years, from 2018–2020.

The camps are offered on a first-come, first-served basis and held at a large mid-south university campus. A typical day for students begins at 7am with breakfast and a bus ride to their first campus experience and ends at 10:30 pm with lights out. In between, students have scheduled courses and informal learning activities. Each informal activity typically lasts 1.5 hours per day for the five-day camp. The remainder of a student's day is spent in information sessions to learn about applying to college, study habits, dorm life, clubs and social aspects of the university, and listening to guest speakers. After their 6:30 dinner, students participate in educationally responsible social activities and STEM immersion experiences.

Demographic data for the most recent years of the Aggie STEM summer camps are given to provide an example of the students who participated in the physics class offered from 2018–2020 and therefore the STEM PBL that is the focus of the current study. In 2019, two classes of physics were offered. Seventeen students enrolled in each class, 34 in total. In those two groups, 17 (50%) students were White (non-Hispanic), 5 (14.71%) students were Hispanic, 3 (8.82%) were Asian, 3 (8.82%) were African American, and 6 (17.65%) students identified as "other." The race/ethnicity breakdown of the students was like that of other years. Of the 34 students in the physics classes, 31 were male and 3 were female. This gender distribution is different than other years. For example, in 2018, there were 21 male students and 10 female students enrolled in the camp's two physics classes. For all three years, the students ranged from 6th to 12th graders, with most of the students in 10th grade. All the students were from Texas.

The STEM PBL described in this paper was developed and tested in the Aggie STEM summer camps of 2018, 2019, and 2020. This was done through collaboration between the teacher (first author) and researchers (other authors). As a major participant in classroom action research, the teacher actively taught and reflected upon teaching practices throughout implementation. The teacher has 4 years of experience teaching physics in a STEM summer camp setting as well as a master's degree in mathematics. He has also served as instructor and teaching assistant for courses for undergraduate pre-service K–12 teachers for three years.

2.8. Observations of the Daily Use of DIME Maps and STEM PBL

The full STEM PBL activity took place during five 1.5-hour classes over the course of the five-day camp. During that time, students used DIME maps to research new vocabulary, formulas, and connections to inform their designs; designed and built prototypes; predicted, tested, and reflected upon results; upgraded their designs into final models; and competed for prizes.

In the following section, we provide a further breakdown of the lessons administered to the students in the physics course in a day-by-day basis and make connections to the engineering design model described previously. We also discuss how the DIME Map system was utilized to improve learning. This report represents a collection of naturalistic observations made by the teacher/researcher team to address the classroom action research question regarding how DIME maps can be integrated into a STEM PBL activity. Note that all timing comments are suggestions based on three years of experience teaching this activity eight different times. Timing can depend largely on the comfort level of the teacher, engagement of the students, and constraints of the classroom.

2.8.1. **Day One**

Day One began with an icebreaker (15 minutes). The teacher and students introduced themselves and learned interesting STEM-related facts about each other. The teacher asked probing questions to learn about students' backgrounds in physics. Students then took a prior knowledge quiz (15 minutes). This quiz helped the teacher identify what the students remembered from their science and physics classes. Once prior knowledge was assessed, the teacher was better able to scaffold what students knew to what they were learning throughout the week.

Next, an overview of the class was given (10 minutes). During this time, the teacher gave the project description: build a spinning object designed to compete in 5 categories: longest spin time, highest angular velocity, highest moment of inertia, most structurally sound, and most aesthetically pleasing. This part was analogous to a client specifying the criteria for the desired product to begin an engineering design process. The teacher then gave a brief overview of the concepts that would be explored. Concepts included angular displacement*, angular velocity*, angular acceleration, moment of inertia* (a.k.a. rotational inertia), centripetal forces, centrifugal force, angular momentum*, rotational kinetic energy*, and possibly torque and gyroscopic precession (asterisks indicate critical topics).

In order to aid in their exploration of physics concepts, the DIME map was introduced (15 minutes). During this time, students created an account on the DIME

Map server and followed instructions given by the teacher to open the map. Figure 2.3 shows students learning to use the DIME map. The teacher guided students through major features of the DIME map, including clicking (to navigate through the textbook), dragging, hiding, deleting, and adding elements of the map.

Figure 2.3

Students Using the DIME Map During a Research Phase

The students were then given time to research (15 minutes). It may be a good idea to encourage students to explore and write notes in their engineering journals about angular displacement, angular velocity, and angular acceleration (if time permits). During the research phase, students identified potential design constraints that could affect their final designs. Some students noted that other spinning objects have equally distributed weight around the axis of rotation. Others investigated how more weight further from the axis of rotation seems to make an object spin longer. These observations and remarks from students not only influenced their design, but also allowed students to make connections between the math and science concepts to real world applications, exercising and expanding their problem-solving skills and creativity (Bicer et al., 2019). Throughout the week-long activity, students were encouraged to note formulas, units, examples, and connections to things they have encountered before.

Students ended the first day in the ideate phase of the engineering design process (20 minutes). Students looked at the building materials available and sketched design ideas. During this time, the teacher walked around, asked why students chose certain elements of their design, and gave prompts to encourage discussion and engagement in this process. We have learned that this process is critical if you need to run a shorter version of this STEM PBL. There are things that would be very hard for the students to know before testing their designs. For example, attempting to glue objects directly to the outside of the bearing usually failed. This fact can be learned by trial and error, discussion of practical considerations about structural integrity, or the teacher explaining how such attempts have failed in the past.

2.8.2. **Day Two**

Day Two began with the students using the DIME map to research new topics (25 minutes). Students explored concepts such as moment of inertia, which is an object's tendency to resist changes in angular velocity. Demonstrations and hands-on stations helped to reinforce conceptual understanding. This was especially true for such a foreign concept as moment of inertia. We highly recommend using the following demonstration, easily performed with household items. The teacher took two similar broomstick handles, taped a water bottle to each end of one of the broomsticks, and then taped two more water bottles near the center of the other broomstick. The teacher then directed students to grip the broomsticks in the center and rotate them back and forth and note which one was easier to rotate. Because both broomsticks had the same mass, the only difference was the distribution of mass about the axis of rotation. For further topics to explore with demonstrations, we suggest angular momentum, law of conservation of angular momentum, and rotational kinetic energy as natural extensions of the topics the students cover each day. The DIME map can help teachers and students alike visualize the connections between concepts like these.

Armed with research on these new topics, students then returned to the ideate and analyze ideas phases of the engineering design process (15 minutes). The ideate phase allowed students to practice creative and divergent thinking (Bicer et al., 2019) to explore alternative creative designs that could potentially satisfy the demands of the task. At that point, the students had enough understanding to engage in discussions about what design considerations might make a spinner spin longer or faster. Several steps of the engineering design process then blended together as students alternated between research, creating ideas, and selecting the best ideas (see Figure 2.4).

Figure 2.4

Students Researching, Ideating, and Analyzing Ideas

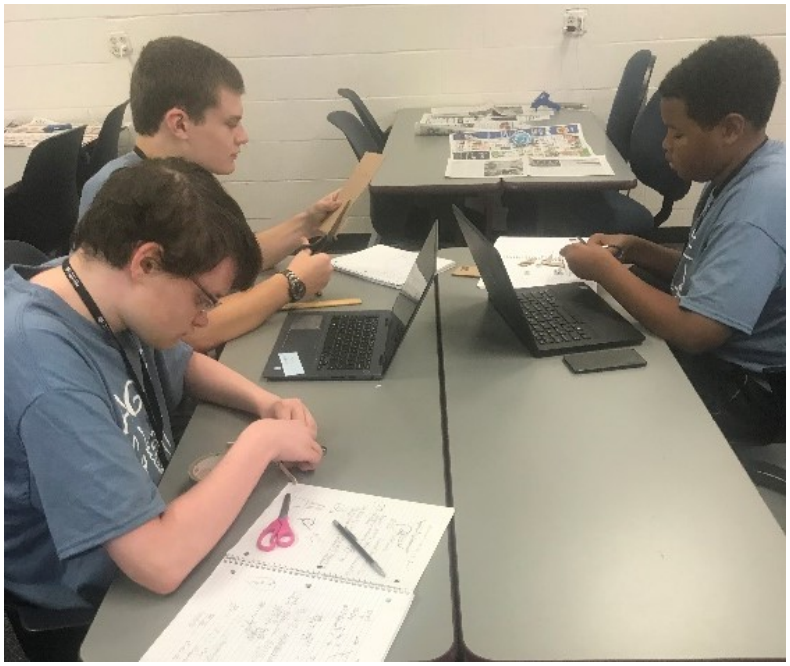
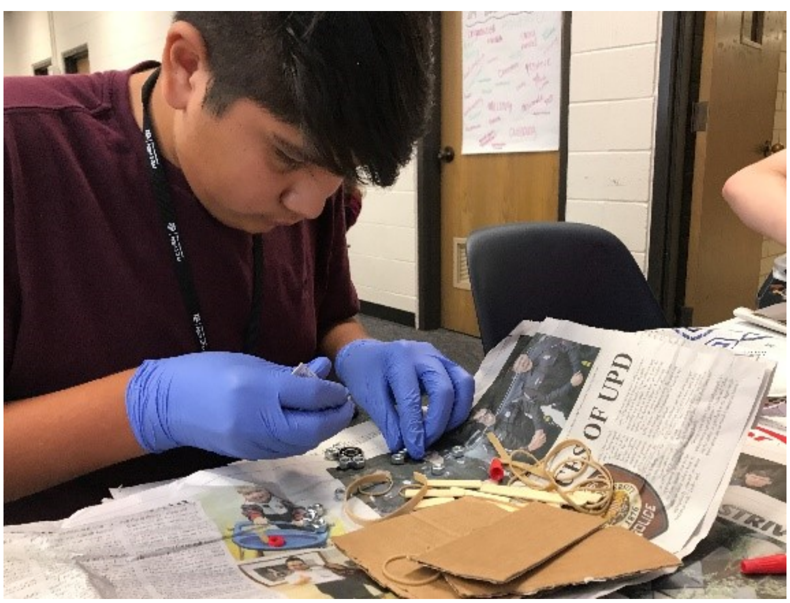


Figure 2.5

A Student in the Build Phase



Students spent the rest of the time beginning to build their spinners using the available materials (50 minutes). Special instruction may be necessary for use of certain materials, including super glue, popsicle stick saws, and epoxy, as well as the proper way to handle bearings. Figure 2.5 shows a student working during the build phase with the available materials.

2.8.3. **Day Three**

Day Three began with the class using the DIME map together (30 minutes). During this time, the teacher asked review questions and conceptual understanding questions, and the students searched for associated concepts to answer. Next, the class researched two new concepts, centrifugal and centripetal forces, and their implications for designs. At this point, the teacher shared a video of a fidget spinner exploding from being spun too fast by an air compressor. The students learned that their builds must be structurally sound to withstand the internal forces that threaten to rip spinning objects apart.

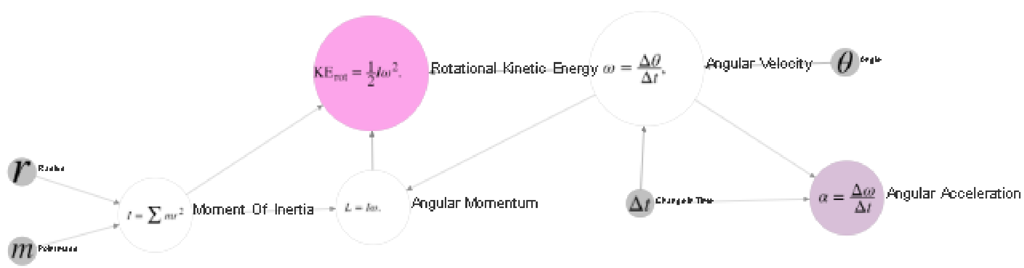
The class ended with plenty of time to continue building (60 minutes). During this time, some students were able to begin spinning their objects and note problems such as weak connection points, asymmetric distribution of mass, and crafting materials that accidently found their way into the center bearing, causing unwanted extreme friction or complete lockup of the spinner. Students used this time to reflect upon and address these concerns and any others that arose during this lengthy build session.

2.8.4. **Day Four**

Day Four began with the students making a custom DIME map using the drag, hide, delete, and add element features (30 minutes). This process helped to ensure that students had identified important information in the map and were able to filter out the parts that were not. By designing their own maps, students found their individual maps more meaningful, and therefore more useful. An example of a student-created map can be found in Figure 2.6.

Figure 2.6

A Student-Created Concept Map Using the DIME Map System



Next the class discussed how to measure angular velocity and how to estimate moment of inertia (30 minutes). To encourage students to think critically about how to measure angular velocity, the teacher asked how one might measure linear (or traditional) velocity of a running student. Connections to measuring distance over a given time interval or measuring the time it takes to run a given distance will lead students to come up with solutions. Some students tried to measure the number of rotations of their spinning objects in a given amount of time. Others tried to see how much time it took to make a certain number of rotations. In either case, it was nearly impossible to physically measure a fast spinning object by eye. Therefore, the class needed to come up with an alternative.

Students attempted to research solutions. Some resources suggested measuring the frequency of oscillating sound near the spinner or measuring the frequency of interruptions of a laser pointing through the spinner and into a detector. Luckily, there is a much cheaper and more accessible method. Most popular cell phones have cameras that allow for slow motion video capture at one-fourth or one-eighth speed. By marking one leg of the spinner with colored tape, students were able to physically count the number of rotations a spinner makes in slow motion. It is important to note that many slow-motion cameras capture video at full speed at the beginning and slow down after about half a second. Therefore, care must be taken to measure accurately.

With one student recording, one student holding the spinner, and a stopwatch in the background of the video, groups were able to measure the angle velocity of their spinners following given instructions: 1. Spin the spinner, 2. Start recording, 3. Start the stopwatch, 4. Stop recording after the stopwatch hits 5 seconds, 5. Count the number of rotations made between the stopwatch starting and 5 seconds, and 6. Divide that number by 5 to get the average rotations per second (convert to radians per second if desired).

The remainder of the time was used to continue testing and refining designs (30 minutes). At the end of this phase, most students had created a final product ready for testing and measurement. Because of the openness of the task, students were able to creatively explore multiple designs (See Figure 2.7).

Figure 2.7

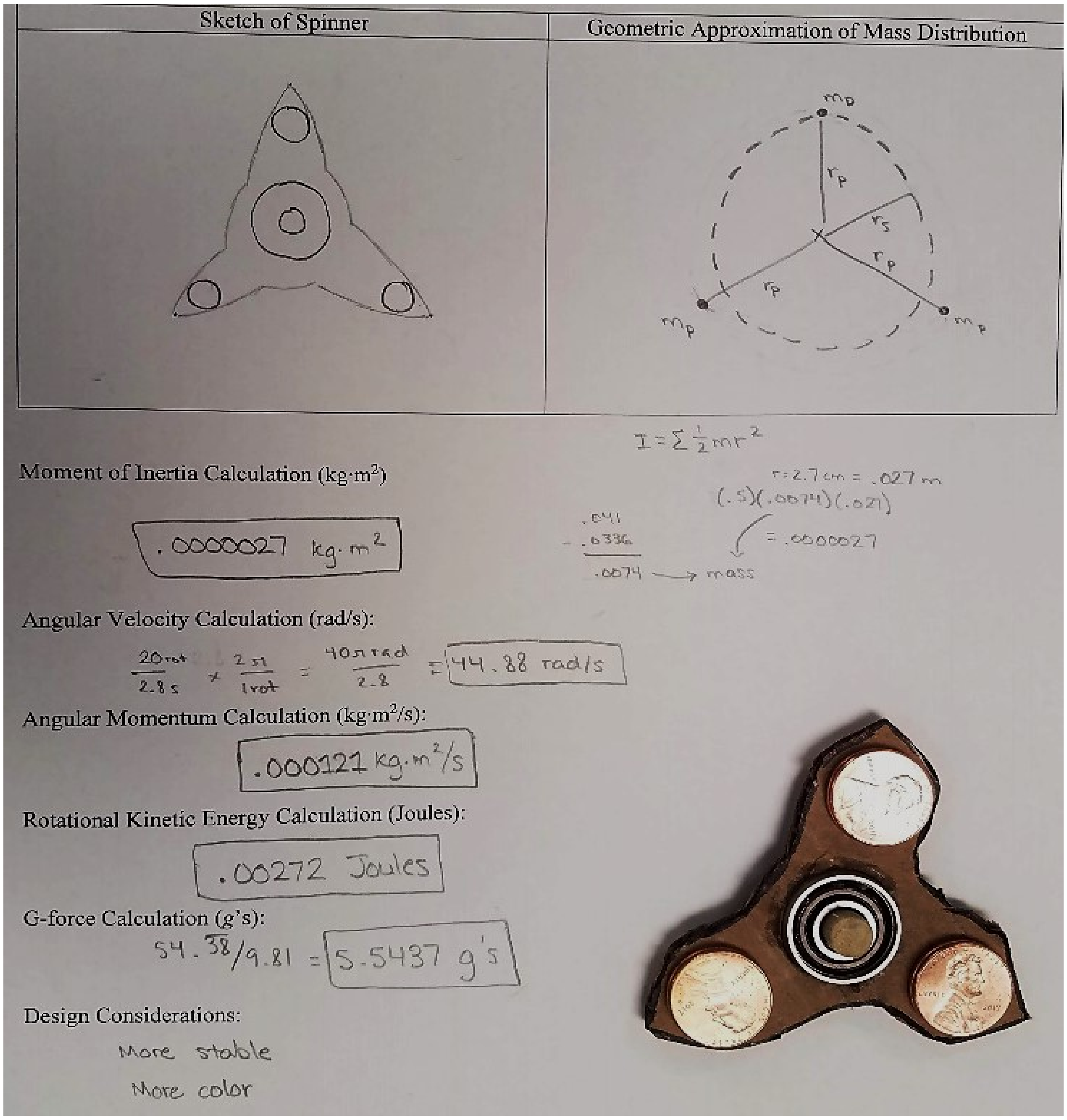
Multiple Creative Designs as a Result of STEM PBL

2.8.5. **Day Five**

Day Five began with final adjustments to the built spinners and a final write-up about the design of their spinners (45 minutes; see Figure 2.8). In the process of completing the final write-up, students engaged in the communicate and reflect phase of the engineering design process. Students discussed with each other what aspects of their design they focused on. Some mentioned the ways in which they designed their spinner to spin faster. Others mentioned the connections between angular momentum, moment of inertia, and spin time for their spinning objects. Students helped each other measure the angular velocity and estimate the moment of inertia of their spinners. The process of estimating moments of inertia was taught to students. The total moment of inertia about an axis is equal to the sum of the individual contributions of moment of inertia by each mass. As shown in a student's work in Figure 2.8, stacks of pennies were considered point masses with measurable mass and radius from the axis of rotation. These stacks of pennies contributed a significant portion of the total moment of inertia. Students also estimated the contribution from the remainder of the mass by subtracting the weight of point masses and the weight of the bearing from the total weight of the spinner. They used a formula for moment of inertia of the remaining mass by approximating the geometric shape of the mass assuming even distribution. Once a student had estimates of their spinner's angular velocity and moment of inertia, they calculated its angular momentum and rotational kinetic energy. Comparing these values to those of other spinning objects helped students make meaningful connections.

Figure 2.8

Final Write-Up Sheet for Students to Communicate and Reflect on Design Process



Next, students competed in contests and compared calculations (45 minutes). After competing for longest spin time, the class discussed what design considerations helped improve spin times. This also doubled as time for students to engage further in the communicate and reflect phase of the engineering design process. Students then compared their measurements of angular velocity and moment of inertia and again discussed what principles were at play. Awards were given to students whose spinners had the “highest angular velocity” and “highest moment of inertia.” Finally, the class voted on “most structurally sound” and “coolest” awards. By engaging in the final contests and discussions, and writing up their design sheets, the students practiced the communication and reflection step in the engineering design process.

2.9. Evaluation

Through this classroom action research study, we worked as a teacher/researcher team to develop a strategy for implementing the STEM PBL activity and maximizing students’ use of DIME maps to research and explore new concepts and engage with the engineering design process. Based on our observations and semi-structured interviews with focus group participants, we identified several key features of the DIME maps that, when used within a STEM PBL activity, allowed students to engage with the information in their textbook, retain key course concepts, and learn how these concepts were interrelated.

For students in the focus group, the DIME map functions as a literal map for learning that allows students to quickly navigate to and read about related topics in the textbook. One student recalled how the DIME map and textbook were displayed side-by-side with the DIME-map on the right, “it shows you different topics. You can click on it and it'll tell you about it a bit and you can just click on each circle and it tells you, it gives you some information on the left, on, like, the textbook.” Each DIME map is a complete summary of a chapter or the entire book, depending on the view, and is linked to the textbook. By clicking on a concept in the DIME map, students can go directly to the introduction of the concept in the book, which helps them to make connections and bridge understanding. The DIME map is presented alongside the PDF textbook, and clicking on the map navigates to the corresponding section of the textbook in the PDF display. One student said of using this feature, “When I couldn't find something because I didn't know the word or name, I would just click it [the symbol] and it would take me there [to a place in the book dealing with what I clicked on]… I could kind of figure it out on my own.” Students felt that being able to find the information in the book and so sometimes being able to read ahead helped make concepts clearer. One student remarked, “The main thing was just being able to click on things and, like, open them up in the PDF so you can read about it… no matter where in the book it was.” This primary feature of DIME maps satisfied the need for navigation functions in interactive electronic textbooks (see Choi & Lam, 2018). Students seemed to feel comfortable using the DIME map to both control their own learning and facilitate their understanding.

Second, students were able to manipulate the DIME maps, rearranging nodes and hiding concepts or links to focus on key concepts. Importantly, each of the individual user interactions, such as clicking, dragging, and searching, were recorded as click analytics, which can provide large data sets to analyze students’ efforts, focus, and use of interventions in future studies (Liberatore et al., 2020). Students used these interactive features to rearrange the information in ways that were meaningful to them (see Figure 2.6). One student noted how “everyone sees it different ways” and “That’s how I rearranged it," referring to their rearrangement of the map. By rearranging the DIME map, students were able to create a representation that more closely followed the way they understood the information and the way new information fit with their prior knowledge.

As a graphic organizer, DIME maps helped students to visualize connections between knowledge. Studying and creating concept maps has been shown to lead to deeper, more meaningful learning (Ausubel, 1968; Hill, 2005; Novak, 1998). One student described their experience researching topics using the DIME map the following way: "It has a graphic organizer type of panel on the side where you can see the different links that all the concepts have to different other concepts and definitions, ideas and stuff. And then you can, you can focus on the concepts on the right." Another student commented how the DIME map is "like a chart with math concepts and other concepts that are related to it." By presenting the core mathematical concepts contained in the chapter in a single map, the DIME maps allowed students to "see everything;" a feature that students described as "very simple, but in a good way. I just like how I can see all the connections." Another student, when asked how they felt about the DIME maps, expressed,

> I liked DIME maps because it had, like, all the information there and easy to get to. With, like, everything showing how they're connected… What I liked about it mostly was because everything was, like, well organized. So I could, if I was wanting to learn more about the topic, I could like see how everything's connected.

As an alternative visual representation of the knowledge contained in textbooks, DIME maps allowed for better assimilation of new concepts into existing knowledge structures by more closely resembling the interconnected nature of knowledge.

Students were metacognitively aware of their learning using the DIME Map. Students expressed this idea in many different ways but characterized the process through various aspects of the tool. For example, in a discussion on angular momentum, a student explained how he would attempt to explore the concept: “I'll go to... I'll search for linear momentum.” The learning step then would typically involve rather dense vocabulary and often a difficult to comprehend definition. The student explained the definition well though: “It's the product of a system's mass multiplied by velocity and directly proportional to the direction of the object's mass…” Despite the complexity of the subject matter under investigation, the student believed that the DIME Map lowered the threshold of acquiring new knowledge and that it could make the content more readily understandable.

The use of the DIME Map also allows students to link both text and equations, but, most importantly, salient diagrams or graphical information is also preserved, thereby maximizing students’ ability to draw their own conclusions and express their understanding in their own terms. The ability to create their own definitions also empowered the students in their learning and allowed them to make the learning more direct and require less effort. One student mentioned how before DIME maps, they would often search Google when encountering a new concept. However, with DIME maps, “you could eliminate that second Googling step, if I don't know what linear momentum is by using, like, just simple terms, like break it down into the basic form of having the linear momentum definition within that sentence maybe or something to that equivalent [like in the DIME Map]". Using the DIME Map provided several affordances, first, it linked all the learning about a topic regardless of where it appeared in the book (graphical, text, and algorithms), it reduced dependency on outside and less-efficient sources, and, finally, it provided students with the ability to have more control over how they learn.

As a self-guided learning tool, DIME maps are particularly situated to assist in learning, especially when students are exploring knowledge at their own pace, such as in STEM PBL. Students expressed their appreciation for having the DIME map to help with the research phase. For example, one student said, "I just really liked you giving us the tools to find the information and having us get the information." The DIME map helped that student to visualize, search for, and apply knowledge to the design and build of their spinning object. Yet it was the design of the object that helped students make concrete connections between their learning and the real world. One student commented, "I feel like at the beginning I was kind of confused, but then, like, while making the fidget spinner made, … it like brought everything together." For the students who participated in this activity, the DIME map and STEM PBL served complimentary roles. The DIME map helped students make connections between concepts, while the STEM PBL helped students make connections from concepts to experiences and observations. In this way, DIME maps and STEM PBL worked hand-in-hand to engage students in meaningful learning.

2.10. Conclusion

There are a few main takeaways for teachers and researchers interested in implementing DIME maps, STEM PBL activities, or both in their own classrooms. As an educational technology, DIME maps helped students make connections between and within their knowledge, assisted in navigating the textbook and self-guided research, and allowed students to personalize the map to fit their individual learning needs.

The key principles of engineering design can be found throughout the STEM PBL activity. By building on these engineering design principles, STEM PBL activities have the potential to improve students' learning, interest, and engagement in STEM and 21st century skills (Bicer et al., 2019; Morgan et al., 2013). An added bonus in this STEM PBL activity was how students enjoyed the collaborative nature mixed with individual research time. One student noted that "half of it felt like a 'class-class' as it should be. And then half of it was, you know, like fun time with your group." In the STEM PBL activity presented in this study, students engaged in all parts of the engineering process from the identify problems and constraints phase to the communicate results phase. By utilizing a design phase and reducing the numbers of trial and error opportunities, we noticed that students were more careful and less likely to make errors. When given less time and trial and error attempts, students worked harder to make sure each build phase was used as efficiently as possible. Through this process, we were able to observe the students plan carefully and efficiently, a staple benefit from learning using the engineering design process (Morgan et al., 2013). Throughout the

STEM PBL activity described in this paper, we observed students engaging in the engineering design process.

Finally, we would suggest that the use of DIME maps and STEM PBL together can be a powerful tool for any content in physics, science, or STEM in general. From our observations, we believe that DIME maps can be used to their greatest potential when exploring content with large amounts of mathematical variables, expressions, formulas, and equations intertwined with the physical concepts. DIME maps can assist in the research, ideate, and analyze ideas phases of the engineering design model. The characteristics of DIME maps make them perfect candidates for boosting self-guided learning. Second, the use of DIME maps enabled students who were unfamiliar with the concepts to visualize the interconnected nature of and relationships between physics concepts. Students commenting on how using DIME maps helped them to see how "everything is connected to everything," illustrated the way that the DIME map assisted students in making connections within their knowledge. This finding was consistent with prior research that has shown that students are better able to make meaningful connections when using concept maps as opposed to rote memorization (Cliburn, 1990; Novak, 1998; Novak & Musonda, 1991). Thus, we were able to observe how DIME maps and STEM PBL could be implemented together to improve students' engagement in the engineering design process and understanding of concepts.

2.11. Limitations and Practical Implications

There are four interrelated implications for this study. First, this activity is an example of the potential for artificial intelligence to scaffold learning in ways we have not yet imagined. Second, once children are freed from linear presentations of knowledge, they show a great deal of autonomy over and identity with the content they are learning. Third, the instrument pushes the limits on how to achieve a truly customized learning plan for every student in class. This instrument bridges language, learning styles, and memory issues without stigmatizing students who learn differently or at different rates. Finally, the instrument's ability to develop maps and allow flexibility in learning by encouraging students to customize it creates a learning efficiency that cannot be duplicated by book indices or using only tabs to create physical links to facilitate learning. These four key practical outcomes lay a foundation for continued work and the unpacking of these ideas through small, targeted studies where specific aspects are controlled and outcomes are measured.

These outcomes are limited to the sample and setting from which the data were gathered. This work should not be generalized to the population as a whole or to groups of students who are not inquisitive about learning, reluctant to use technology, or who have physical conditions not conducive to using electronically generated and presented DIME maps. Further work needs to be conducted to determine if there are any benefits for second language students or students with minor to moderate reading difficulties or comorbid reading and mathematics difficulties. We propose that further studies investigate the use of DIME maps in STEM PBL. As technology, and artificial intelligence in particular, becomes more advanced, we expect DIME maps to become a powerful tool in the processing and teaching of mathematical material from textbooks.

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3. A FIRST LOOK AT EFFECTIVENESS: DIME MAPS—THE EVOLUTION OF CONCEPT MAPS

Graphic displays of information have long been critically examined for their ability to improve students' learning and retention of new information. Traditionally, graphic displays of information include concept maps, flow charts, semantic maps, tree diagrams, and other organizers dealing with the display of information graphically in a meaningful way (Guo et al., 2020; Horton et al.,1990). In education settings, graphic displays of information can be provided as advance organizers prior to students' learning to provide a road map for potentially challenging material (Ausubel, 1968; Chuang & Liu, 2014; Githua & Nyabwa, 2008). Indeed, there is evidence that when introduced to the material beforehand, students learn more from lectures covering difficult concepts (Schwartz & Bransford, 1998; Stelzer et al., 2009). Concept maps have also been shown to reduce cognitive load by providing students an alternative visual representation of connections between ideas or concepts (Hill, 2005; Novak, 1998; Özmen et al., 2009; Stull & Mayer, 2007). The cognitive theory that underpins most research on the use of graphic organizers is that advance organizers allow students to link previous knowledge to new knowledge, creating knowledge schemas (Ausubel, 1968). The intervention used in this study can be considered an automatically computer-generated concept map or graphic organizer of mathematical knowledge. Underlying this study is the idea that students are better able to meaningfully learn when they can interactively engage with material and connect new learning to prior knowledge and future goals.

3.1. Background and Framework

Having the ability to access, apply, and connect various mathematical equations is useful in helping individuals understand the topics that these equations describe. This is because equations are a way of writing and making sense of formal mathematical concepts (Wang & Liu, 2017). Graphic organizers have been used to assist students in making sense of new, formal concepts across many subjects, mathematics included. Graphic organizers have the potential to improve learning and retention by making new, abstract material more concrete and by making connections between prior knowledge and new information (Ausubel, 1968; Dexter et al., 2011; Mayer, 1979). By building on a strong foundation of educational theories and practices, we explore the use of Dynamic and Interactive Mathematics Expressions (DIME) maps to enable students to meaningfully learn and engage with their educational materials.

3.1.1. **Theoretical Framework**

The theoretical underpinnings of this study can be traced to two origins: the assimilation theory of learning and research on concept maps. The assimilation theory of learning is based on the idea that meaningful learning occurs when students assimilate, or anchor, new concepts into their existing prior knowledge structure (Ausubel, 1968; Ausubel & Robinson, 1969; Ausubel et al., 1978; Gardee & Brodie, 2021). This theory frames the world around us as a web of interconnected thoughts and ideas. Through this lens, rote memorization is found to be a poor substitute for meaningful learning, as it requires the learner to memorize a fact or formula without connecting it in any meaningful way to their past experiences or knowledge. Knowledge acquired during rote learning has a weak association with one's pre-existing knowledge structure and is, therefore, not stable enough to remain in long-term memory.

Developed in accordance with the assimilation theory of learning, concept maps provide opportunities for students to visualize the interconnections between the concepts they are presented (Novak, 1990, 2004). With concept maps, concepts are represented as nodes and relationships between ideas are represented as links. The resulting map shows the interconnections between these ideas (Shahbari & Abu-Alhija, 2018). Developments in technology have allowed concept maps to become interactive, further increasing the potential for student engagement in learning; and both traditional concept maps and interactive concept maps have been associated with positive gains in cognitive and affective measures (Schroeder et al., 2018). By building on the research of these components, we propose that DIME maps have the potential to improve student learning.

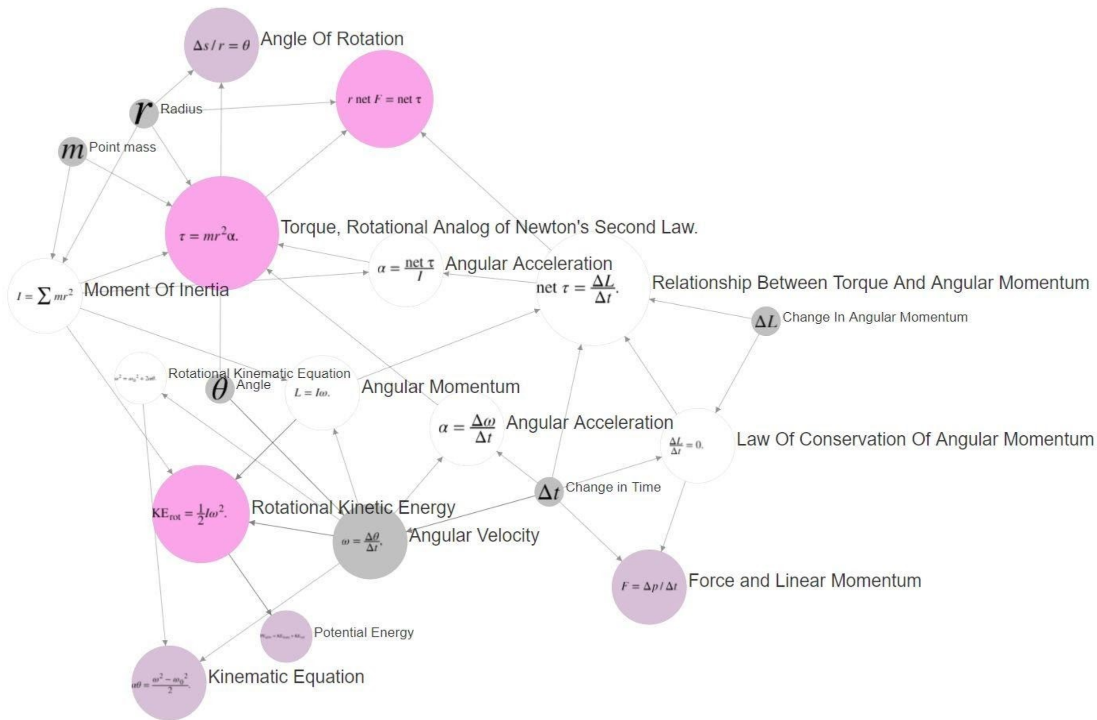
3.1.2. **DIME Maps**

With the intent to help students learn mathematical ideas, a team of computer science engineering researchers developed the DIME Map system (Beyette et al., 2019; Rugh et al., 2021; Rugh et al., 2019; Wang et al., 2018). The DIME Map system provides a road map of interconnected topics and equations. Theoretically, DIME maps, like concept maps before them, should reduce the cognitive load inherent in learning new material, enabling students to acquire new knowledge at faster rates and establish enduring understandings of the interrelationships between their knowledge.

This "road map" of interconnected topics manifests itself through the DIME map, which uses links, arrows, and spatial arrangement to highlight both key concepts and structural relationships (see Figure 3.1). The DIME Map system removes redundant elaborations found in texts and covers only the key fundamental concepts expressed in equations bounded with words. In other words, the DIME Map system finds mathematical objects (e.g., variables, expressions, and equations) and identifies them using the surrounding text, even when there are many other unrelated words in the surrounding sentences. It then automatically creates a map that displays the interconnection of mathematical equations and expressions from this information, specifically identifying the in/out relationship of concepts through the use of arrows. It also uses the semantics established throughout the document to accurately identify and connect elements of the expressions and equations, creating a smooth continuity of meaning across presentations. Previous researchers examined the automatic generation of concept maps using natural language processing (Atapattu et al., 2017; Shao et al., 2020), but the DIME Map system is focused on mathematically based concepts. Additionally, the relationships in a DIME map are well defined in that one concept builds into or is a component of the concept it is connected to.

Figure 3.1

An Example DIME Map

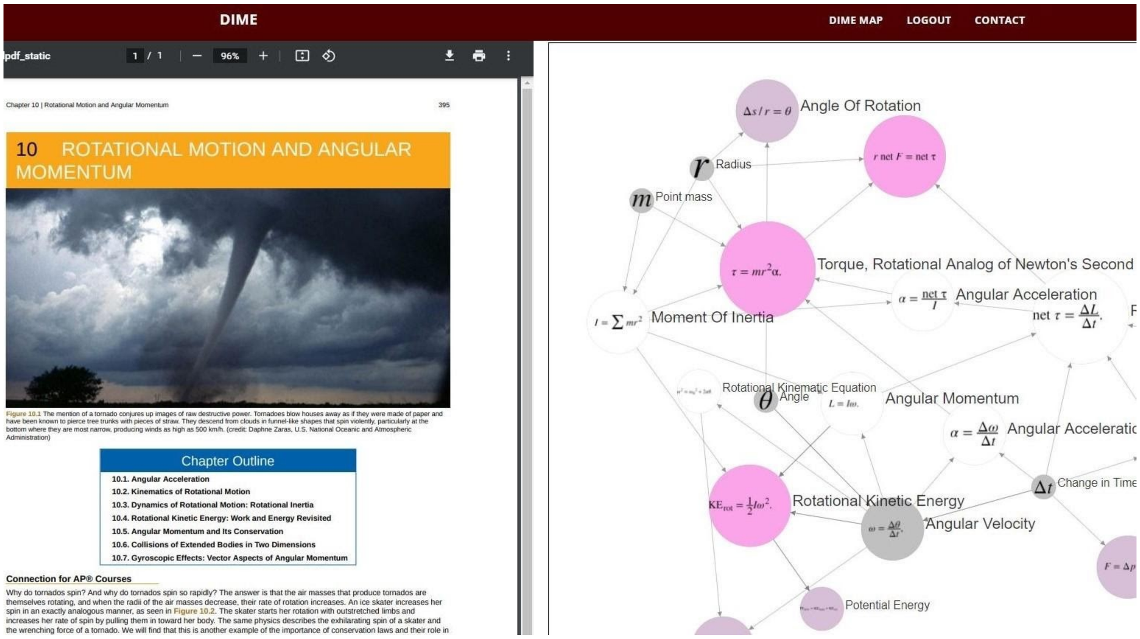


Note. A typical DIME map shows concepts as circular nodes and relationships between concepts with linking arrows.

In addition to being automatically generated, DIME maps differ from manually constructed and visually static concept maps in the way that users engage with them. Users can customize their maps interactively to meet their own conceptual needs. This is possible because the DIME map is housed inside an elastic container that allows users to see the DIME map displayed side-by-side with the original portable document format (PDF) text document (see Figure 3.2). The elasticity of the map further allows it to hold large amounts of content while also providing a convenient way for users to move the map's display through panning and zooming in towards or out from operations. Furthermore, the placement of the mathematical objects within the map follows the principle of spatial affinity for connected concepts, which is in accordance with humans' spatial perceptions. The density of the nodes can be adjusted to make best usage of the space and avoid overlapping. A user can also customize the spatial arrangement of partial nodes to meet their own conceptual understanding. The nodes are linked back to the text as well, and clicking on a given node will navigate the PDF display to the first occurrence of the associated mathematical concept. Students and teachers can additionally "hide" a node from the map that they regard as less important for the current educational encounter.

Figure 3.2

A DIME Map (Right) and PDF Textbook (Left)

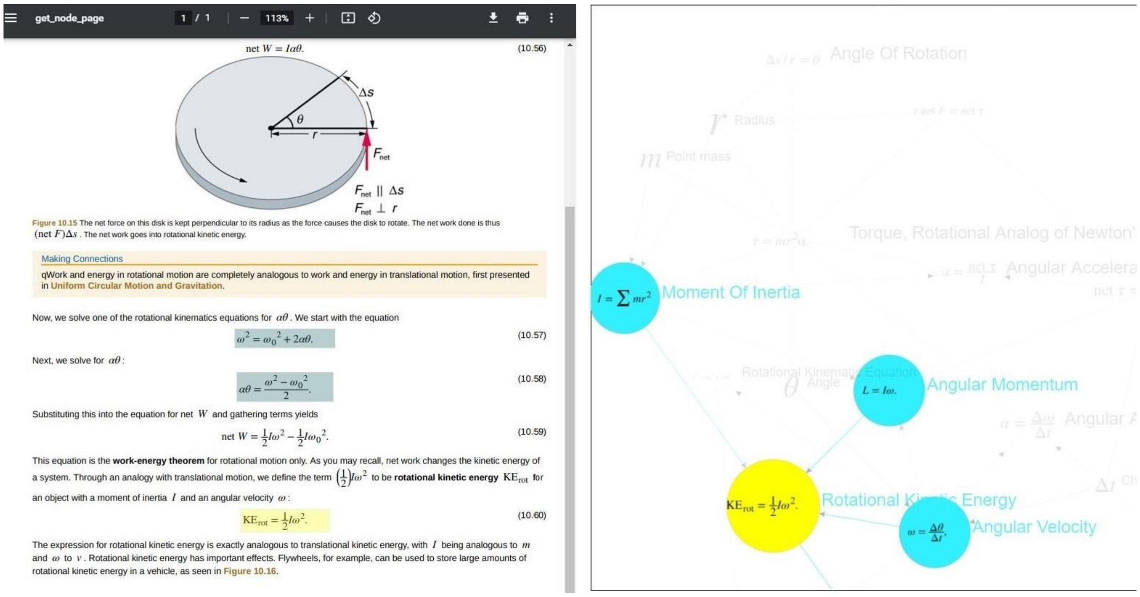


Note. This figure provides a visual example of how a DIME map is displayed next to original text. Not intended to be readable.

Those using the DIME Map system can interact with their maps through multiple features. Users can search for words and mathematical expressions directly to locate certain pieces of information, and matched information found through the search function will be highlighted in both the DIME map and PDF text document. This is because each DIME map is synchronized with the original material through side-by-side displays and color coding. Because of this, users can also navigate to the original materials in the PDF text document by clicking on the mathematical object in the DIME map. Additionally, when studying the building components and usage of certain concepts, students can simply click on a node to focus the map and text on that concept. After the click, the textbook page where that concept is introduced is displayed, mathematical objects directly related to that concept will be highlighted in the DIME map, and unrelated concepts will fade out by using transparency (see Figure 3.3). Finally, a snapshot of the user-made arrangement can be taken for personal records or for sharing with others. If space is limited, as with a tablet or phone, the PDF text document or the DIME map can be hidden. Redundancy input options, such as buttons, are provided for users using touch screens or touch pads. DIME maps are dynamic and interactive and, therefore, potentially more engaging and useful than traditional concept maps. The purpose of this small-scale pilot study was to demonstrate DIME maps are an appropriate alternative to traditional instruction that does not utilize the DIME Map system.

Figure 3.3

A DIME Map and PDF Textbook Focused on One Concept



Note. This figure provides a visual example of the navigation feature of DIME maps—clicking on a concept in the map highlights related concepts and navigates the user to the introduction of that concept in the text. Not intended to be readable.

3.1.3. **Research questions**

As computer-generated concept maps, DIME maps already possess the potential to reduce a teacher's workload. The additional dynamic and interactive features, however, suggest potential to improve student learning as well (Rugh et al., 2021). Therefore, we focused on the following research questions:

1. Is there a multivariate relationship or pattern between using DIME maps and two learning outcomes for students: self-efficacy towards learning physics and understanding connections between content knowledge?

2. How do students feel about using DIME maps—what aspects of DIME maps do students consider helpful or harmful to their learning process?

3.2. Materials and methods

We employed a mixed methods design that included a small-scale pretest/posttest control group design for the quantitative phase as well as observational and interview data for the sequential qualitative phase. The subsequent qualitative phase was used to support the quantitative exploration in order to learn more about this novel educational technology and examine the quantitative results; such a design can be expressed symbolically by QUAN → qual to describe the precedence of the quantitative phase, both temporally and in terms of contribution to the outcome (Leech & Onwuegbuzie, 2009; Morse, 1991). The sample (n = 31) included high school students who were randomly assigned into one of two groups: an experimental group that had access to DIME maps and a control group that did not. Both groups engaged in project-based learning (PBL) in order to encounter and explore the mathematical and physical concepts involved in fixed axis rotation. A control group design was implemented to account for other potentially impactful moderators, such as PBL, which has been shown to have a significant positive effect on student learning (Bicer et al., 2015; Chen & Yang, 2019). Posttest scores minus pretest scores constituted participants' growth scores. We then analyzed these growth scores using a multivariate analysis of variance (MANOVA) in SPSS 24, which is appropriate for the analysis of two closely related dependent variables (Warne, 2014). In this case, a MANOVA is justified because self-efficacy in physics has been found to be positively related to knowledge outcomes in physics (Sawtelle et al., 2012). In-class observations and sequential qualitative interviews allowed us to examine the results of the quantitative portion of the study.

3.2.1. **Participants and setting**

There were 31 high school participants who signed up to take a physics class during a summer camp designed for science, technology, engineering and mathematics (STEM)-oriented students in 2018. Students chose four of eight possible classes to engage in while attending the summer camp. They were then immersed in 1.5-hour daily sessions for each selected classes (four or five days total). Students who selected the physics class were randomly assigned to one of two groups: 15 were assigned to the control group (five female students and ten male students), and 16 were assigned to the treatment group (five female students and eleven male students). Both the treatment and the control group made use of PDF textbooks during the class, but the treatment group were also able to use the DIME Map system alongside the textbook. The physics behind fixed-axis rotation comprised the content covered in the class. None of the students had taken a physics class in school. Detailed demographics for the participants in this study were as follows: 10 (32%) female and 21 (68%) male; nine (29%) Hispanic or Latino and 22 (71%) White (non-Hispanic); 10 (32%) in 9th grade, seven (23%) in 10th grade, 11 (35%) in 11th grade, and three (10%) in 12th grade. An overall sample size of 31 was sufficient for use with a simple MANOVA (Jafar et al., 2016). Still the sample size was small, so there was concern whether we could examine interaction effects without significant likelihood of a Type II error. The a priori power analysis—with an estimated effect size of $f^2(\lambda) = 0.25$, $\alpha = .05$, and power of 80%—indicated a sample size of five participants per group was sufficient.

The physics class was taught by a single instructor who was observed by at least two, but on some days three, researchers whose primary focus was to ensure that lessons were presented to the two groups in exactly the same fashion, with the same pacing, and using the same pedagogical strategies, ensuring continuity of the lessons. The purpose of using the same instructor was to avoid scripting, to reduce the cognitive load on the instructor, and to afford a more uniform implementation. The instructor was trained to use DIME maps by the development team, and the instruction for teaching students about the DIME maps was co-developed by the instructor and the research team.

3.2.2. **Data sources**

One pre/posttest for both *Self-efficacy* and Connections in Knowledge (*Connections*) was administered. The instrument was first vetted by research faculty in the Colleges of Science and Education who evaluated validity and alignment to the lesson content and objectives. There were four questions related to Self-efficacy, posed as 5-point Likert-type questions (see Appendix A). There were also five questions testing for Connections in Knowledge (see Appendix B). The Cronbach's alpha was sufficient across Self-efficacy ($\alpha = .8348$), and across Connections ($\alpha = .4286$). Self-efficacy was robust, yielding a strong positive internal consistency estimate.

Finally, at the end of the week-long intervention, we conducted semi-structured interviews with students who had used the DIME maps. By following an interview protocol (Knox & Burkard, 2009), we were able to pre-emptively consider what questions we wanted to ask and uniformly ask the same questions to multiple participants. Some of the interview questions were included to inform the research team as to ways DIME maps could be improved in the future. See Appendix C for the full interview protocol. We conducted the interviews face to face. Three students were selected based on their high levels of interactions with the DIME maps throughout the week. For the purpose of confidentiality, they will be referred to under the pseudonyms Alice, Bailey, and Chris. We recorded audio from the interviews to later transcribe and analyze.

3.2.3. **Data analysis**

The quantitative data were analyzed using MANOVA, and the qualitative data helped to explain the results. The use of MANOVA to analyze the relationship between the treatment and both Self-efficacy and Connections are justified because these two dependent variables are closely correlated (Freedman, 1997; Warne, 2014). We also reported effect sizes because they are often referred to as the single best reporting strategy for quantitative methods and need not be reserved for when reporting a statistically significant result (Capraro, 2004; Fritz et al. 2012). To account for relatively small sample size and encourage future meta-analyses of these results, we calculated Hedges' (1981) bias corrected effect size (*g*) using the following equations:

$$s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{(n_1 - 1) + (n_2 - 1)}}$$

$$g = \frac{M_1 - M_2}{s_p} \times \left(\frac{N - 3}{N - 2.25}\right) \times \sqrt{\frac{N - 2}{N}}$$

For these equations, we used the sample size (n_1), mean (M_1), and standard deviation (s_1) of the first group; sample size (n_2), mean (M_2), and standard deviation (s_2) of the second group; and total sample size ($N = n_1 + n_2$) to calculate pooled standard deviation (s_p) and Hedges' bias corrected effect size (g). A standard statistical significance level, $p = 0.05$, was set for all analyses in accordance with traditional practice in education research.

For the qualitative phase, we used deductive thematic analysis to analyze the interview data to further investigate the findings from the quantitative analysis. Thematic analysis can be used "both to reflect reality and to unpick or unravel the surface of 'reality'" (Braun & Clarke, 2006, p. 81). We considered our initial interpretations of the quantitative analysis results to inform our assumptions about the nature of the qualitative data. We used a theoretical thematic analysis approach in that our coding of the qualitative data analysis was guided by our second research question. Themes were identified using a semantic approach by looking at specifically what the participants said (Braun & Clarke, 2006). To begin, three researchers transcribed the interviews and carefully read each response to identify meaningful units of text—words, phrases, or sentences that stood out to the coders as related to our second research question in some way. Next, we grouped the units together into tentative categories, discussed the categories, and decided on a final set consisting of five major themes. We then interpreted the themes to theorize their importance in relation to the quantitative findings and prior literature.

3.3. Results

The primary interest of this exploratory study was to determine if using DIME maps in some way mediated learning for the treatment group as compared to the control group. After the data were collected and analyzed preliminarily, it also became interesting to examine the effects of the DIME maps by gender. After the quantitative analysis, the interviews were examined using thematic analysis. The three coders identified five major themes that were related to the second research question.

3.3.1. **Quantitative results**

By using two-sample *t* tests, we determined that there were no statistically significant differences in pretest scores across *Self-efficacy* and *Connections* in Knowledge between the treatment and control groups nor between the female students of each group. Therefore, the pretest and posttest data were combined to form new variables, Self-efficacy growth and Connections growth (see Table 3.1), by subtracting the total for the pretest from the total for the posttest for each category. Additionally, boxplots indicated no univariate outliers, and tests for Mahalanobis distance indicated no multivariate outliers. Therefore, the MANOVA was a suitable choice for the data analysis. The adjusted R^2 effect sizes were small and relatively unimportant. Therefore, the random assignment and the pretest allowed us to conclude with reasonable certainty that any obtained effects were due to the intervention and use of the DIME map.

Table 3.1

Descriptive Statistics for Subgroups' Growth

	Self-efficacy Growth						Connections Growth			
	Control			Treatment			Control		Treatment	
	n	Mean	SD	n	Mean	SD	Mean	SD	Mean	SD
F	5	-.200	2.049	5	2.800	1.789	.200	.447	1.600	1.140
M	10	2.100	3.143	11	1.273	1.849	0.700	0.823	1.455	0.934
All	15	1.333	2.968	16	1.750	1.915	0.533	0.743	1.500	0.966

Note. F = Female, M = Male, All = Males and Females Combined

Results from the MANOVA showed that statistically significant differences existed between groups (See Table 3.2). The overall model was statistically significant ($p < .05$), indicating a statistically significant difference in Self-efficacy growth and Connections growth based on the predictor variables: group (control vs treatment) and gender (female vs male) ($F(6,52) = 2.38$, $p < .05$; Wilk′s $\Lambda = 0.616$). There was not a statistically significant interaction effect between group and gender on Self-efficacy and Connections ($F(2,26) = 2.60$, $p = .094$; Wilk′s $\Lambda = 0.834$). The lack of a statistically significant interaction effect indicated that the treatment may not have had different effects based on gender.

Table 3.2

Results of the MANOVA on Self-efficacy Growth and Connections Growth

Source	Wilk's Λ	df	F	p
Model	0.616	3	2.38	0.042
Residual		27		
Group	0.696	1	5.67	0.009
Gender	0.983	1	0.22	0.801
Group by Gender	0.834	1	2.60	0.094
Residual		27		

The standardized effects were computed using Hedges' *g* for all variables, including those that were not of primary interest to provide study information for future meta-analyses (see Table 3.3). Because no statistically significant differences were found between groups and subgroups on the pretest, effect sizes for multiple comparisons were calculated. DIME maps had positive effects on Self-efficacy growth (g = 0.158) and Connections growth (g = 1.052). In particular, female students who used DIME maps showed greater growth in Self-efficacy (g = 1.260) and in Connections (g = 0.466) than female students in the control group. Finally, it is important to note that while a significant interaction effect between group and gender was not detected in the MANOVA, different outcomes were observed in the two groups when comparing female students and male students. In the control group, male students outperformed female students in Self-efficacy growth (g = 0.707) and Connections growth (g = 1.082). However, the opposite was observed in the treatment group, wherein female students outperformed male students in Self-efficacy growth (g = 0.737) and Connections growth (g = 0.129). These results suggest that using DIME maps may actually have had a larger effect on female students than on male students, and this finding warrants further investigation in future studies.

Table 3.3

Hedges' Bias Corrected Effect Sizes (g) for Growth in Self-efficacy and Connections

		Hedges' Bias Corrected Effect Sizes (g)	
	n	Self-efficacy growth	Connections growth
Control vs Treatment (Overall)	31	0.158	1.052
Control vs Treatment (Female students only)	10	1.260	0.466
Control vs Treatment (Male students only)	21	-0.297	0.930
Female vs Male (Control group)	15	0.707	1.082
Female vs Male (Treatment group)	16	-0.737	-0.129

Note. Positive effect sizes indicate the second named group scored higher than the first.

3.3.2. **Qualitative results**

The three authors, including two professors and a graduate student, performed the initial coding of the interview transcripts. Once all three had initially examined the transcripts, we met together to discuss the list of codes until 100% agreement was achieved. We came up with 52 unique codes that described the interviewees' words, phrases, and sentences. From those 52 codes, we identified patterns and sorted them into five themes consisting of how DIME maps were considered a pre-assimilator of knowledge, led to improved accessibility, involved high interactivity, were a tool for empowering learners, and displayed initial complexity. We identified these themes as being particularly connected to answering our second research question. We then examined, in order of prevalence in the original interviews, the themes and their underlying codes and units, or codable portions of the transcribed interviews.

3.3.2.1. Pre-assimilator of knowledge

The first major theme we noticed was that DIME maps served the students as a pre-assimilator of knowledge—a tool that helped digest or breakdown complicated concepts, making them easier to learn. During the automatic creation of DIME maps, the DIME Map system breaks down the information contained in a PDF textbook chapter or document section and presents concepts along with the relationships between those concepts. In the DIME map, students can see how introductory concepts, usually in the form of individual variables, build into more complex concepts or equations. Those complex concepts are themselves connected to each other and to further complicated concepts. While describing how the map showed the connections between individual equations, Alice explained that using the DIME map "makes it easier to understand how everything has an effect on everything." Implied connections between concepts became explicitly represented in DIME maps. In this way, DIME maps served as an advance organizer of knowledge. Advance organizers have been found to be particularly useful for novice learners (Gurlitt et al., 2012), which can help explain why our novice students valued how DIME maps organized information for them. During the interview, Chris explained the following:

> It allowed me to see the formulas which was always nice. Usually, when I read books like that, I have to find the formulas to write them out. This kind of just did that for me... It would definitely make learning through textbooks a lot easier.

Chris' description of how the DIME maps reduced effort connects directly to prior literature on advance organizers and reduction of cognitive load. Cognitive load theory assumes that learners have limited working memory (Baddeley, 1986, 1992; Kirschner, 2002). By presenting the interconnected nature of concepts, DIME maps reduce the extraneous cognitive load of finding and organizing formulas. Thus, students have access to more available working memory to focus on understanding the application of the concepts presented and any connections that they do not yet fully understand.

3.3.2.2. Improved accessibility

The second theme we identified was that DIME maps offered improved accessibility. There are many abilities that some students may lack and which we normally discuss when it comes to accessibility (visually impaired, language impaired, etc.). However, there is another, cognitive ability, which may be lower or higher for individual students due to varying opportunity and propensity. It is here that we see the DIME map making a larger difference. When asked whether DIME maps helped to learn differently, Alice responded:

> I feel that it did [help me to learn differently] because once you see something visually, um, it kind of helps you get a better understanding. Because I'm a visual

learner, or visual and kinesthetic, so it helps me when I move the mouse around, and I see like how all the terms are connected to one another.

Alice appreciated having a visual organizer of knowledge with which she could interact. This result corresponds with decades of research that have shown graphic organizers of knowledge to be valuable for improving students' learning (Dexter et al., 2011; Horton et al., 1990). DIME maps helped students to see knowledge in different ways that they had never thought of before. For Bailey, this benefit was especially noticeable when extra information was hidden. She commented, "It made it so much simpler when you pressed on it and it only showed a few terms and you could actually look at it. It was better when it showed it like that." Complex concepts and relationships between concepts were made approachable and, therefore, more accessible. Chris confirmed this notion when describing how he thought that using DIME maps "definitely made it faster. I'm not sure it improved the learning, but it definitely made it faster which would allow you to learn more in less time." While he was not sure whether the depth of learning was improved, Chris noticed that he could learn faster using DIME maps. Graphic organizers in general have been shown to facilitate faster comprehension of study materials than text alone (Robinson, 1997; Ward & Marcketti, 2019). Students who used DIME maps noticed that DIME maps assisted in visualizing connections between knowledge and decreased time required to learn new material.

3.3.2.3. High interactivity

All of the interviewed students described the high level of interactivity available with DIME maps and how this improved their learning experiences. Alice was particularly impressed with the features of DIME maps, describing the benefits of an interactive system over a static textbook:

> Yeah, I feel the textbook, it doesn't have as much… you can't really touch it or interact with it as much. It was really helpful to have [the DIME map] in front of you and see it and see if you move this strand here and if you move that strand there or whatever, you got to see, like, where it had impacts. Whereas in the textbook it would be really straightforward and you really wouldn't understand it as much. This kind of just sped up and made the learning process easier for me.

Visual connections alone were not enough for Alice. She enjoyed being able to actively manipulate the map and watch how the strands would move. This feature helped Alice understand concepts were robustly interconnected.

Students expressed appreciation for other features of DIME maps as well. Bailey and Chris both expressed appreciation for the navigation and control features of the DIME maps. Bailey mentioned that she enjoyed "Clicking and being able to see connections. Clicking and then the textbook would make it go to that spot. That was good." Chris mentioned "Being able to highlight things and see where they are on the page." Both of these students could decide what they were interested in learning about and then use the DIME map to navigate the textbook and focus their learning. Another example of interactivity of the DIME maps was visible in its search feature. "I thought it was really good for finding one section," Bailey commented. Searching found instances of term occurrences in both the textbook and the map. These features correspond to the several types of interactivity described by Moreno and Mayer (2007) for multimodal learning environments: controlling, manipulating, searching, and navigating. However, it is important to note that interactivity alone is not sufficient to promote deep learning. The behavioral activity promoted by interactive elements does not necessarily accompany cognitive activity required for deeper learning (Moreno & Mayer, 2007). While we have seen that DIME maps offer high levels of interactivity, future research is needed to investigate what multimodal design principles are present in DIME maps and support deep cognitive processing.

3.3.2.4. Tool for empowering learners

Students expressed that using DIME maps generally empowered them as learners. A powerful example of this was seen with Alice, who decided to use the DIME maps to help her roommates:

> I have my roommates, and they are in the same course as me, so all three of them, they were in a separate class that didn't have the map. So I found myself a lot at home, we would like look over our notes or whatever, and I found myself kinda helping them a little bit just because I understood it and they were still a little stuck on it... I showed them it for a little bit. They thought it was very difficult. They thought the map was difficult just because it had like so many things. Like strands. But once they kind of got the gist of it, it was good and it helped them as well… Also, they didn't know that some of them were connected. So like once they saw the chains light up, they were like oh!

Alice was empowered by the DIME maps to feel comfortable with her own understanding and use the tool to then teach her roommates. Peer teaching has been shown to be linked to higher self-efficacy for learning (Brannagan et al., 2013; Irvine et al., 2018) and deeper learning of concepts (Evans & Cuffe, 2009; Irvine et al., 2018). Personal performance accomplishments or mastery experiences have been shown to also improve self-efficacy (Bandura, 1977, 1997). That is exactly how Baily recalled her experiences using the DIME maps.

Throughout the class, students were asked to research specific concepts and share what they learned. When Bailey wanted to understand the concepts, she set out to know what the formula was and how it could be used. Bailey mentioned how "It was good to find the formulas and then you could see what connected to what and then branch out from there." For Bailey, DIME maps made the first step of the learning process easier. Through using DIME maps, Bailey was able to successfully explore relationships between concepts and learn more deeply. Even though she expressed having some difficulties early on, Bailey described how "At first, I was a little confused. But then after some time, I definitely liked it… I figured it out, and I understood." Her confusion was replaced with successful navigation of the complex material. This mastery experience helped Bailey feel more confident in her abilities to learn. Students who used DIME maps became more empowered learners.

3.3.2.5. Initial complexity

Students revealed that they initially found the visual presentation of DIME maps complex and confusing. When first opened, the DIME map originally showed all of the mathematical variables, expressions, and formulas contained in the physics textbook chapter (see Figure 3.2). One of the biggest lessons we learned was that this presentation of all of the mathematical objects and relationships was overwhelming for students. Bailey's comment that "At first, I was a little confused" was later followed by "It was just a little confusing to me because of all the… just seeing all the equations at once and then being surprised." She noted that one possible source of her confusion was because she "had never done any physics before." Without prior encounters with these concepts, she found the display of all of the concepts somewhat overwhelming. Chris also drew our attention to this issue in his interview when he described his first impressions of the DIME map:

> It was kind of messy. It looked like a really useful tool, but it looked kind of messy and all jumbled up. There was this one point when I first opened it, that there were so many lines you couldn't see which line went to where.

When there are so many objects and links between objects, students could not understand which concepts were connected. Thus, the benefits of DIME maps were overridden by confusion.

Alice also found the DIME maps to be complicated at first, stating, "Well, I thought it was really complicated, um, because of all the equations and symbols I didn't know. But once I started learning about it, I realized how it was kind of... all just connecting your learning." Too much information was clearly presented on the screen without a gentle introduction. Students initially experienced a heavy cognitive load. Excess visual load can lead to cognitive overload, where students' construction of internal connections between visual and verbal information is disrupted and some information is lost (Mayer, 1997). Interactive materials are especially prone to the issue of presenting students with too much cognitive load (Moreno & Mayer, 2007). For the students who engaged with DIME maps, the initial confusion was eventually replaced with understanding. Alice told us the story of this progression: “Well, I thought it was really complicated, um, because of all the equations and symbols I didn’t know. But once I started learning about it, I realized how it was kind of... all just connecting your learning.” This seems to bring about a sense of expertise and educational independence—Alice was able to learn independently and then turn that knowledge into something she could translate as she taught her roommates. Both concepts, expertise and independence, seemed to be fueled by the self-efficacy that grew as an amalgamation of small events situated in the nexus of real-life instruction and affordances from artificial intelligence.

3.4. Discussion

Through this study we extend the research in three broader areas. First, it addresses important issues with the development of mathematical or symbolic language (see Esteve, 2008; Goldin & Kaput, 1996; Hiebert, 1988; Silver, 2017). By pre-assimilating the knowledge contained in textbooks and presenting it as an alternative visual representation, DIME maps make mathematical and symbolic language more accessible to students. As students interact with DIME maps, they observe the nuanced interplay of mathematical and symbolic language, once in the textbook and again in the DIME map. In this way, DIME maps have the potential to facilitate the development of a stronger understanding of the semantics and syntax of mathematics (see Capraro et al., 2010). Although people commonly claim that mathematics language is foreign to them, only recently has the importance of the disciplinary language been viewed as a potential gatekeeper to student mathematical success.

Second, this work addresses the broad research agenda of reading in the mathematics content area (see Moschkovich, 2007). By providing an alternative, visual representation of written text, DIME maps have the potential to improve learning for students who are not well served by traditional textual reading. The removal of barriers between lengthy expository text and student comprehension and translation into mathematical symbols means that DIME maps can be considered to be an equitable and accessible tool for underserved populations (see Moschkovich, 2013) or people with comorbid reading difficulties or dyslexia. In the control group for this study, male students outperformed female students on both growth in self-efficacy and growth in ability to make connections between tangentially and hierarchically related concepts. However, the use of DIME maps led to the exact opposite results in the treatment group, in which female students outperformed male students on both constructs. This interaction effect was not statistically significant, but due to the large differences in effect sizes, we suggest that replication studies measure the varying effects by gender of using DIME maps. Additionally, our sample was not sufficient to support conjectures about underserved students or those with comorbid reading difficulties, so future research might be directed toward these populations to determine if this affordance could make a meaningful contribution. The overall potential for this tool to address both the rate of learning and the depth of learning provides broader impacts across many different student populations, including potentially those with learning difficulties, language minorities, and underserved populations.

Finally, this work addresses how connections between the text intended to teach mathematics and symbolic representations emerge for students (see Godino et al., 2007; Hiebert, 1988). DIME maps visually display the interrelationships between concepts. Students using DIME maps can simultaneously read about a concept and its related formulas while visually seeing the connections displayed on the right side of their screen across chapters and how those concepts develop. The intellectual importance of the software lies in the ability to better understand how students learn and think while browsing and learning from an interactive model.

Historically, concept maps and graphic organizers have been limited in how students can make use of them to meet their own individual academic needs. It is common to find concept maps and graphic organizers that are predesigned for students as an advance organizer or that are co-developed with a group of students as a classroom instructional strategy. The limitation in these forms of concept maps and graphic organizers lies in the lack of self-agency and customizability: these organizers are singular constructions designed for the class and are therefore not customizable to any particular student's needs. Such types of organizers are static and fully dependent on who designed the instruction or led the development. Although there is nothing wrong with this method, it is a proxy measure aimed at understanding whether concept maps improve student learning. Only now has technology afforded students the ability to interactively work with a textbook chapter to build dynamic and customizable maps of the content they are learning.

Like concept maps before them, DIME maps can provide a means to reduce cognitive load. Mathematics is becoming more complex, and the syntax and semantics of algebra often integrate aspects of other formulae (Capraro et al., 2010; Rupley et al., 2011). To approach such complexities, students using DIME maps can easily track a complex formula back through its development. For example, angular momentum is equal to moment of inertia multiplied by angular velocity. This relationship may sound simple, but it consists of several mathematical relationships that students must already know and understand. By using DIME maps, students are able to visualize and interact with the connections between concepts and meet immediate personal learning needs. Through future research analyzing the effects of DIME maps on larger groups and across more variables, DIME maps may prove to effectively improve understanding, retention of knowledge, and self-efficacy for high school students in mathematics.

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4. IMPROVING SELF-EFFICACY WITH COMPUTER-GENERATED CONCEPT MAPS: ANALYSIS OF USER INTERACTIONS

Electronic and online learning have become mainstream and essential adaptions to the demands of the modern engineering classroom. Many students in primary to tertiary classrooms learn key course concepts via lessons mediated through technology and educational tools that provide e-learning content, interactive materials, and instantaneous feedback loops. However, the growth in popularity of technology-enhanced learning comes with a need for a better understanding of students' engagement with such learning tools. Through the research presented by Garrett et al. (2019), we have a better understanding about the institutional methods, activities, leadership, and individual roles necessary in effective online learning. Unfortunately, we still lack an understanding of the software tools being developed to bridge the gap between physical and virtual learning environments. As a result of this increasing demand and understanding of online learning, we have developed the Dynamic and Interactive Mathematical Expressions (DIME) map software tool to assist teachers and students in or out of the classroom by automatically transforming mathematical textbooks into dynamic and interactive concept maps. Initial qualitative results on DIME maps (Beyette et al., 2019; Rugh et al., 2019) showed positive feedback about DIME maps and led to this study, an examination of students' interactions with DIME maps and their self-efficacy in physics.

Learning new concepts often relies on a student's attitudes, which can be broken down into three components: cognitive, affective, and behavioral (Ostrom, 1969; Rosenberg & Hovland, 1960). The cognitive component is related to the student's individual thoughts about the concepts being learned (Akinsola & Olowojaiye, 2008; Mensah et al., 2013), while the affective component is related to their feelings or emotions about learning new concepts (Ingram, 2015), which fuels their engagement in learning new concepts and is influenced directly by the cognitive component. Lastly, the behavioral component of attitude relates to how the student responds when assimilating and evaluating new concepts (Akinsola & Olowojaiye, 2008; Mensah et al., 2013). As a result, research indicates that a student's attitude towards learning is directly related to the student's ability to learn, that is, their ability to understand, remember, apply, analyze, and evaluate new knowledge (e.g., physics concepts and mathematical equations; Akinsola & Olowojaiye, 2008; Grootenboer, 2003; Ingram, 2015; Kerby, 2017; Lipnevich et al., 2011; Mensah et al., 2013; Mutohir et al., 2018; Rybczynski & Schussler, 2013; Sanchal & Sharma, 2017). However, understanding how to properly affect student attitude, and in particular self-efficacy, towards learning is an ongoing topic of investigation requiring innovative uses of technology and research findings on learning.

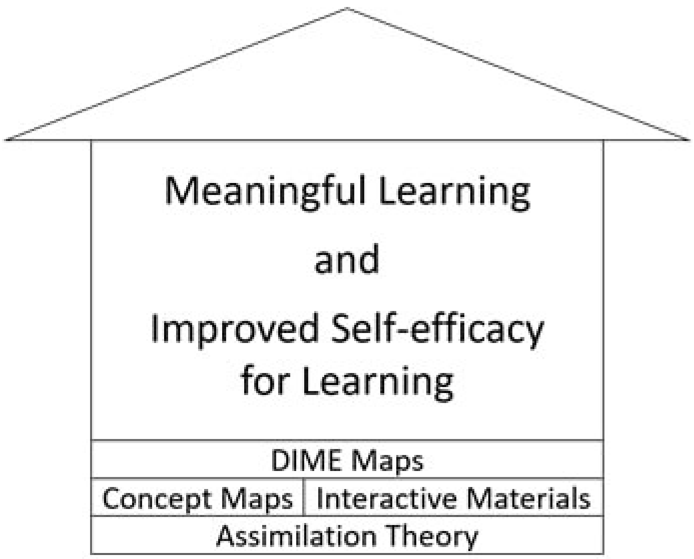
4.1. Theoretical Framework

The theoretical framework that guided and continues to guide the development of DIME maps and their use in education is built on a foundation of research on assimilation theory of learning, concept maps, and interactive material (see Figure 4.1).

These components position DIME maps as educational tools to improve learning and self-efficacy.

Figure 4.1

Theoretical Framework for DIME Maps



Note. DIME maps are built on a foundation of assimilation theory, concept maps, and interactive materials to promote improved learning and self-efficacy.

4.1.1. **Self-Efficacy**

For the purpose of this paper, we follow standard definitions of self-efficacy. We use self-efficacy to refer to a person's perceived belief about their ability to produce positive results in a given area (Bandura, 1994, 2006). Self-efficacy has been shown to be closely correlated with academic achievement or performance (Lane & Lane, 2001; Wood & Locke, 1987). In particular, self-efficacy in physics has been suggested as a statistically significant predictor for success in physics courses (Cavallo et al., 2004; Sawtelle, Brewe, & Kramer, 2012; Taasoobshirazi & Sinatra, 2011; c.f. Gungor et al., 2007). Unfortunately, self-efficacy often remains stable or even drops during physics courses rather than improve (Nissen & Shemwell, 2016). Thus, there is a need for learning interventions that teach physics while improving self-efficacy in physics learning.

There are two types of educational experiences that have been accredited for the development of self-efficacy beliefs in students—mastery experiences and vicarious learning experiences. Bandura and Schunk (1981) suggested that self-directed learning plays a role. When students are in control of their own learning, they set and attain personally meaningful goals. It may be that self-directed learning provides ample opportunities for *mastery experiences*, defined as opportunities for success or failure on given tasks. Mastery experiences in learning generally involve the students actively learning and engaging with their educational materials. As such, mastery experiences have been found to be a strong positive predictor of developing motivation and self-efficacy for learning (Bandura, 1994, 1997; Changeiywo et al., 2011). On the other hand, *vicarious learning experiences* occur when students are observers and not active participants in a given task (Sawtelle, Brewe, Goertzen, & Kramer, 2012). These vicarious learning experiences can involve other students, the teacher, interactive educational materials, or any other modeling of learning, knowledge, or understanding. All that is required is that students are not overtly performing the modeled activity directly (Bandura, 1965). Some researchers have suggested that vicarious learning experiences may contribute to self-efficacy to a greater degree than even mastery experiences (Sawtelle, Brewe, Goertzen, & Kramer, 2012; Sawtelle, Brewe, & Kramer, 2012). Together, mastery experiences and vicarious learning experiences can provide students with ample opportunities to improve in their self-efficacy as a learner.

4.1.2. **Assimilation Theory**

The primary foundation for DIME maps and how they interact with student learning is grounded in the assimilation theory of learning. Meaningful learning requires the development of long-term personal knowledge, and it has been theorized that assimilation is a key component of this process. Assimilation theory states that meaningful learning occurs when students anchor new learning by connecting it, or making links, to things they already knew or have experienced (Ausubel, 1963, 1968; Ausubel et al., 1978; Ausubel & Robinson, 1969). In this way, new knowledge is assimilated or integrated into a person's preexisting knowledge structure (Seel, 2012). As the number of links between preexisting and new knowledge increases, the learner is able to increase the strength of the associations in their knowledge structure. Through this process, new knowledge becomes a stable part of the learner's knowledge structure. The learner is then enabled to make connections between existing components of their knowledge structure and additional or more complex concepts, fostering the process of knowledge assimilation and in fact increasing the speed with which it can occur.

4.1.3. **Concept Maps**

The interconnection of knowledge by relationships can be imagined as a web or map where ideas are represented as nodes and relationships are represented as links. The process of creating such a visual representation is commonly referred to as concept mapping. Based on Ausubel's learning theory, concept mapping was developed to better represent the learning and knowledge structures of children (Novak, 2004; Novak & Cañas, 2008). In a traditional concept map, concepts are represented as nodes and relationships between concepts are represented as lines or links between the nodes. This visual representation of knowledge is a more accurate reflection of the internal knowledge structures imagined through the assimilation theory of learning than the linear representation provided by traditional textbooks. Concept maps are often given as an advance organizer prior to learning so that students can more easily visualize the connections between what they already know, what they are currently learning, and what they will be learning in the future (Nesbit & Adesope, 2006; Schroeder et al., 2018). In this way, concept maps can act as a vicarious learning experience for students; students observe and reflect on the way that the concept map is organized. In addition, studying concept maps may reduce cognitive load for students as it makes the relationships between concepts and the hierarchical structure of knowledge explicit and visible (Nesbit & Adesope, 2006; Novak & Cañas, 2008; Schroeder et al., 2018). In order to capitalize on these attributes, teachers have long used concept maps as a learning tool to improve instruction.

Concept mapping has been shown to be a powerful tool of instruction that can improve student learning over alternatives, such as traditional lectures, outlines and notes, and even comparison treatments (Horton et al., 1993; Nesbit & Adesope, 2006; Novak, 1990). Students engaging in mapping their knowledge have reported strongly improved attitudes about learning (Hall & O'Donnell, 1996; Horton et al., 1993). Through both systematic review (Hartmeyer et al., 2018) and meta-analyses (Nesbit &

Adesope, 2006; Schroeder et al., 2018), concept mapping has been suggested as an advantageous strategy to improve learning. Because of this, additional studies have been conducted in the past decade involving interactive concept maps with a variety of settings, participants, and teaching strategies. Using interactive concept maps has been linked to affective gains (Chen et al., 2019; Hwang et al., 2011). The likely positive relationship between concept mapping and students' self-efficacy for learning justifies exploring advances in concept mapping technologies.

4.1.4. **The Interactive Learning Materials**

Another theoretical foundation for this work is research on interactive learning materials. In particular, the cognitive-affective theory of learning with media (CATLM) theorizes how learning takes place in a multimodal, and generally interactive, learning environment (Moreno & Mayer, 2007). Through CATLM, Moreno and Mayer (2007) described how "prompting students to actively engage in the selection, organization, and integration of new information, encourages essential and generative processing" (p. 316). Interactivity in educational technologies enable students to engage in meaningful learning experiences.

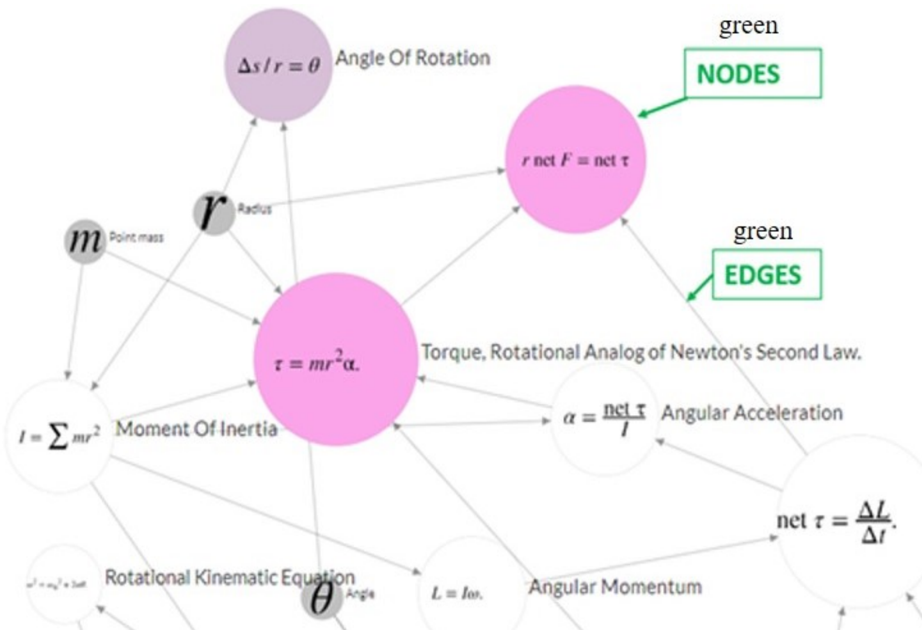
Traditional physics classrooms often consist of a professor leading a lecture and a laboratory session that is intended to enhance the assimilation of the lecture material. However, with the growth of online learning and technology, millennials (Gen Y 1977–1995) and centennials (Gen Z 1996–TBD) often require different teaching methods than those used in previous generations, as they grew up in a predominantly digital environment. Thus, digitally interactive materials have become more relevant in education because of the increased availability of computers worldwide. In addition, studies have shown that online sources of information, such as e-books, increase the average student performance on quizzes by about 16%, exam grades by 16%, project grades by 16%, and can increase lesson effectiveness by 16% when compared to the performance of students receiving only traditional instruction methods (Edgcomb & Vahid, 2014; Edgcomb et al., 2015). As a result, researchers and teachers have developed many interactive techniques and methods to promote and improve learning in physics classrooms, such as tinkering (Conlin & Chin, 2016), MATLAB (Ross, 2018), project-based learning (Bicer & Lee, 2019; Capraro & Slough, 2013), sports (Sanchal & Sharma, 2017), conceptual physics courses (Rueckert, 2015; Smith et al., 2009), and advanced physics laboratory teaching (Kumarakuru et al., 2017). However, obtaining the physical tools and teaching experience required to implement methods such as tinkering (Conlin & Chin, 2016) and sports (Sanchal & Sharma, 2017) may not be readily available or accessible for most physics classrooms. In contrast, computer-based educational technology provides an affordable and accessible alternative for engaging students in interactive media-based learning. Interactive educational technologies allow for multiple opportunities for both mastery experiences through interactive elements and vicarious learning experiences by making explicit connections between new content and earlier text passages (Chi et al., 1994; Gholson & Craig, 2006). In this way, interactive materials have the potential to allow for meaningful learning gains. We hope to explore the relationship between students' interactions with DIME maps and their growth in self-efficacy in physics learning.

4.2. DIME Maps

As computer-generated dynamic digital concept maps, DIME maps provide an interactive and malleable visual learning tool for students and teachers (Beyette et al., 2019; Rugh et al., 2019). As with concept maps, DIME maps have the potential to reduce cognitive load, provide multiple representations of knowledge, and assist students in understanding connections between prior and newly assimilated knowledge, providing a vicarious learning experience where students can observe the connections made between concepts. These connections are derived from three core features that are extracted from the portable document format (PDF) textbook: *mathematical objects* (e.g., equations or expressions), *declarations* (e.g., word labels; Lin et al., 2019), and *semantics* (LaTeX). Together, these core features create the initial DIME map that adapts to teacher and student interactions and feedback. In an example DIME map without the textbook (Figure 4.2), the nodes represent mathematical objects and the edges (e.g., links or arrows) define the relationship between mathematical objects (concepts). Each DIME map is represented as a dynamic digital map that reflects the interconnected relationships between the mathematically based content of a given PDF document. Through DIME maps, students are enabled to freely explore and interact with mathematical concepts they are studying.

Figure 4.2

Image of a DIME Map Without the Textbook



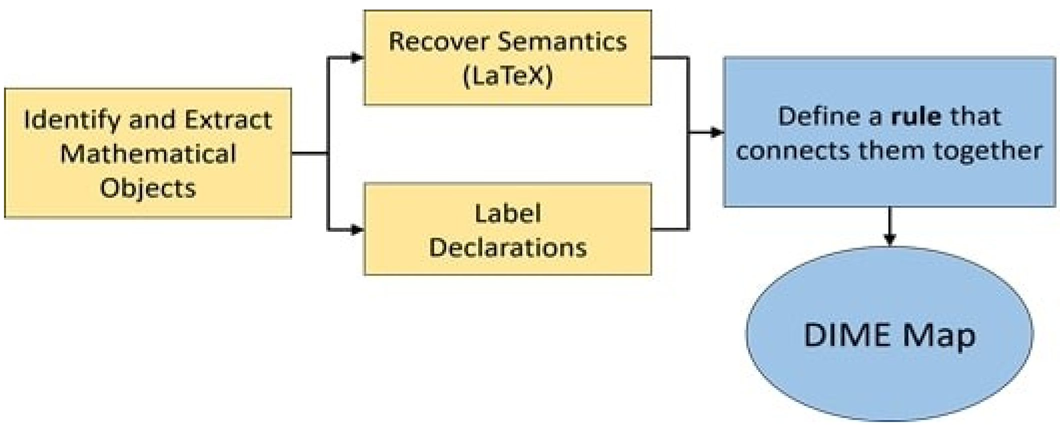
Note. Nodes represents mathematical objects and edges represent the relationships that connect mathematical objects

4.2.1. **Creation of DIME Maps**

The creation of DIME maps begins with identifying the existence of possible mathematical objects in PDF documents, which are generally much different than the natural language used to describe or define each mathematical object. Once identified, the mathematical object can be extracted, as well as its declaration and semantics (Wang et al., 2019). We define mathematical objects as a collection of characters that may represent a mathematical variable, expression, equation, or formula whose semantics (e.g., object meanings, order of operations, and logical syntax) are used to generate the corresponding LaTeX form. Declarations represent word meanings and word relations for each mathematical object, such as a name, identifier, or definition, and are also automatically extracted and assigned to each mathematical object in the DIME map. The mathematical objects and their associated declarations are arranged in an organized manner with links connecting related mathematical objects. Figure 4.3 provides a brief systematic overview of the process used to create the DIME map.

Figure 4.3

Creation of a DIME Map



Note. Rules define the relationship between mathematical objects (concepts)

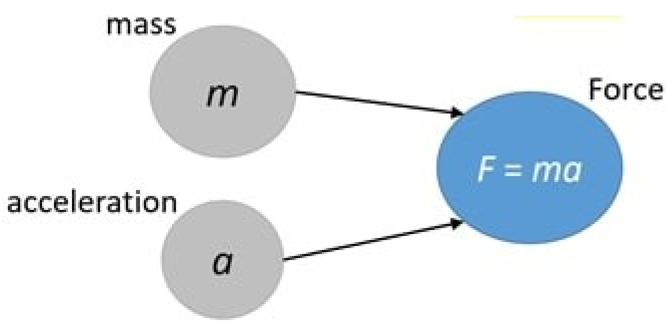
As mentioned in Figure 4.2, edges (e.g., links or arrows) represent the relation or connection that binds two mathematical objects together, creating the final DIME map output. In traditional concept maps as originally defined by Joseph Novak, relationships between concepts are indicated by a word or phrase along the link between them (Novak, 1990; Novak & Cañas, 2008). Similarly, in DIME maps, links (edges) between mathematical objects are understood by the phrase "*build(s) into*," which indicates that a one object is used in the formulation of the equation for the next object. These relations can be thought of as a rule that is defined by humans on how the mathematical objects should be connected together. The rule used during this study is defined as the following: Mathematical expressions or variables that exist on the *right-hand side* of an equation are said to *build into* the mathematical expression on the left-hand side of the equation.

In other words, any expression that is completely contained on the right-hand side of an equation will be connected to that equation by drawing an arrow (e.g., link or edge) from the expression to the equation containing that expression. Many other rules could be imposed to generate a different concept map as long as they can be well defined. It is important to note that an equation is composed of two or more expressions, so if the left-hand side of the equal sign is contained on the right-hand side of a different equation, it will build into that equation.

For example, a textbook might have the following text with an accompanying formula: "<u>Force</u> is the product of <u>mass</u> (m) and <u>acceleration</u> (a) as shown in the equation: $F = ma$." Note that the formula will often appear on its own line in textbooks. Before the DIME map is generated, the computer must first identify and extract the mathematical objects m, a, and $F = ma$ from the sentence and then recover their declarations (labels) and semantics (LaTeX). The declaration for m is mass, acceleration for a, and force for $F = ma$, and each of these represent an individual node in the DIME map. However, the equation $F = ma$ can be a little misleading for the computer, as the expression on the right-hand side of the equal sign may represent the single expression ma or the two expressions a and m. In addition, the declarations themselves may sometimes be misleading, as a single word (e.g. *force*) may have multiple meanings depending on the context (Rugh et al., 2018). Thus, semantics is used to understand the correct logical syntax of $F = ma$. Once the mathematical object and its declaration and semantics are extracted from the PDF document, the relationship rule can be used to connect them together (see Figure 4.4 for an example).

Figure 4.4

Mathematical Concept Map Based on Three Concepts



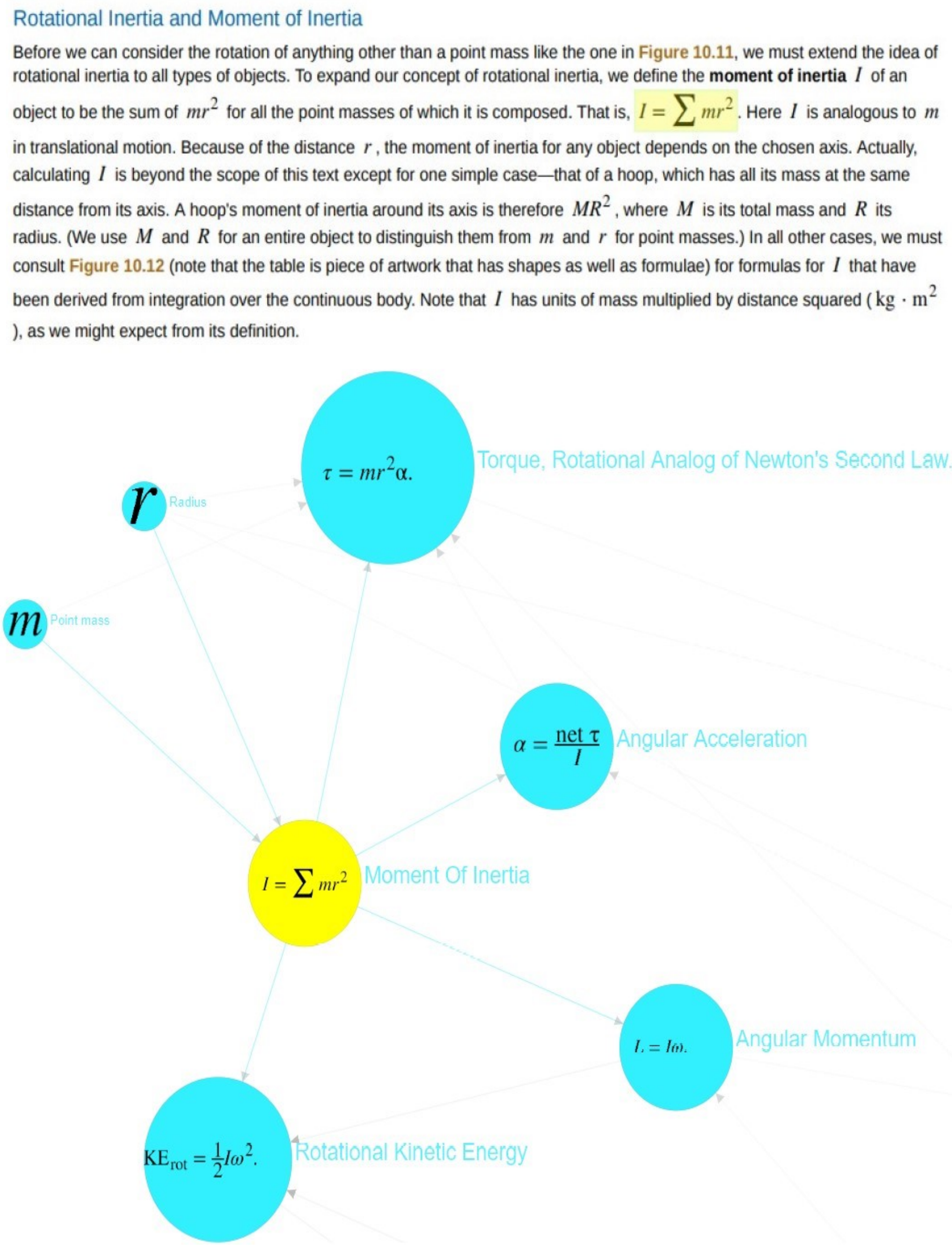
This process continues iteratively for every mathematical object that is extracted from the PDF document, causing the number of relationships between interconnected concepts to increase exponentially as more mathematical knowledge is introduced into the DIME map. To avoid a visually overwhelming and complex graph, additional rules and filters can be applied in order to select the nodes and edges that best reflect the current class objective.

An example DIME map and accompanying text (Figure 4.5) can give insight into what the DIME map system is, how DIME maps might appear to a student using it during class, and what students were using during this study. Each circle or node on the right is a mathematical object that shares a connection to other mathematical objects that they build into or build from. The map can be manually rearranged by students and teachers, and the latest versions of the system automatically adjust map appearances based on prior actions and feedback of students and teachers through machine learning (Beyette et al., 2019).

The map also serves as a new way to visualize and navigate the information included in a traditional textbook or PDF document. Similar to concept maps, DIME maps allow for vicarious learning experiences when students observe the system making connections between concepts within a textbook. However, DIME maps also provide mastery experiences in the form of interactive engagement. Students can actively engage in their learning using the key interactive features of DIME maps, such as navigation. For example, a student can navigate to the location where a mathematical object was first encountered and defined in the textbook by clicking on one of the nodes (mathematical objects). At the same time, the map will reduce cognitive load by emphasizing the selected node (in yellow: *Moment of Inertia*) and its closest relationships (in blue: nodes that are one link away from the selected node), as shown in Figure 4.5. In other words, a hypothetical student using the example DIME map and PDF textbook in Figure 4.5 clicked the yellow node $I = \sum mr^2$, which had the declaration *Moment of Inertia*. Once clicked, the DIME map faded out all other nodes that are not directly related to the clicked node and changed the color of the selected node, reducing cognitive load and allowing the student to focus on the selected node and its interrelated connections, which became highlighted in blue.

Figure 4.5

Example Image of a DIME Map Output (bottom) with the PDF Textbook (top)



Rotational Inertia and Moment of Inertia

Before we can consider the rotation of anything other than a point mass like the one in Figure 10.11, we must extend the idea of rotational inertia to all types of objects. To expand our concept of rotational inertia, we define the **moment of inertia** I of an object to be the sum of mr^2 for all the point masses of which it is composed. That is, $I = \sum mr^2$. Here I is analogous to m in translational motion. Because of the distance r, the moment of inertia for any object depends on the chosen axis. Actually, calculating I is beyond the scope of this text except for one simple case—that of a hoop, which has all its mass at the same distance from its axis. A hoop's moment of inertia around its axis is therefore MR^2, where M is its total mass and R its radius. (We use M and R for an entire object to distinguish them from m and r for point masses.) In all other cases, we must consult Figure 10.12 (note that the table is piece of artwork that has shapes as well as formulae) for formulas for I that have been derived from integration over the continuous body. Note that I has units of mass multiplied by distance squared ($\text{kg} \cdot \text{m}^2$), as we might expect from its definition.

Note. In an actual DIME map, the map and text are presented side-by-side.

4.2.2. **DIME Map User Interactions**

Interactivity is a part of DIME maps from the moment they are generated by the system. Specifically, DIME maps contain several internal interactive features (user interactions), i.e., *searching*, *clicking* and *dragging*, *deletion*, and *hiding*. Note that clicking and dragging is coded as the same user interaction. Additional experimental features included "add node" and "add link," which allowed students to free draw a new node, insert it into the DIME map, and add their own connections to any other node. Students were also able to double-click a node to open a new window that searches Google for different definitions and information about the node's mathematical object. The technological and educational obstacles presented by these experimental features will be dealt with in future developments but are not examined in the current study. Finally, students could search, delete, and hide nodes in their DIME map via a panel displayed above the map (Figure 4.6).

Figure 4.6

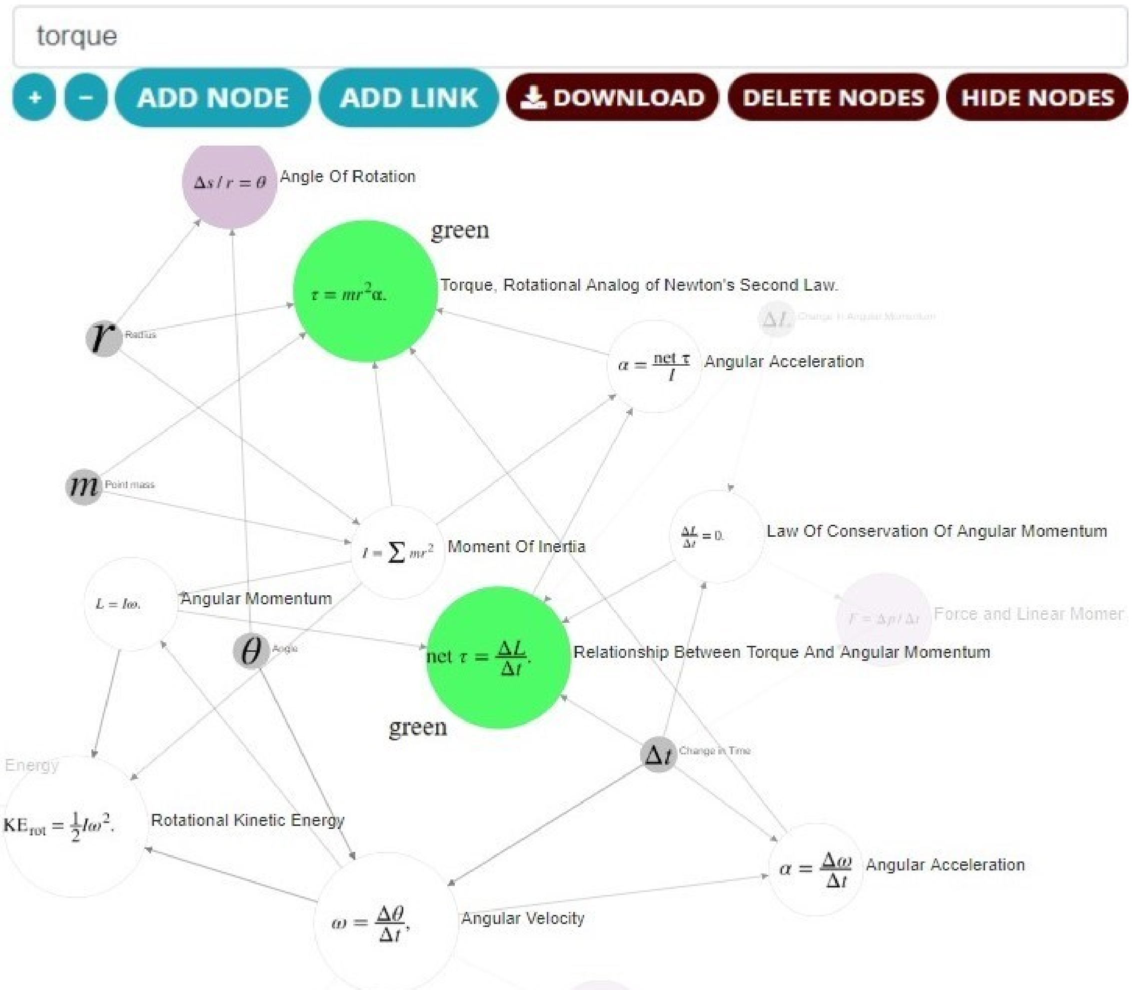
Features Panel, Accessible Directly Above the DIME Map

Searching is related to students typing into the search bar above the DIME map. The searched term is then compared against every node (mathematical object) declaration and LaTeX language. For example, let's say a student wanted to find all nodes with the word *Torque*. They would simply type that word in the rectangle with the

Search term placeholder (see Figure 4.6). The result would change the color of every node that contained the word torque in their declaration to green (see Figure 4.7).

Figure 4.7

Image of a DIME Map After a Student Typed "Torque" in the Search Bar

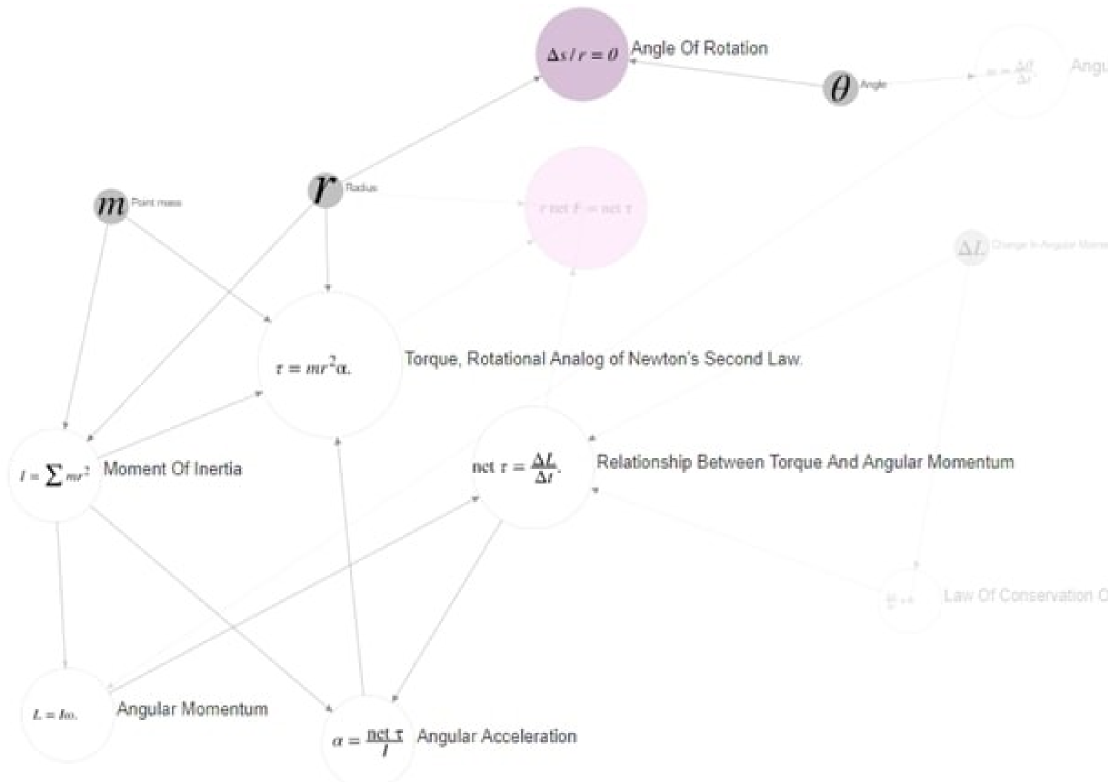


Students often used the search bar to navigate the DIME map when the teacher asked them a specific question on a particular physics concept. The ability to easily search allowed them to quickly identify the related node and "click" it to better understand the physics concept in question.

Clicking on nodes allows students to travel to the first occurrence in the textbook where that node was defined, and the action focuses on that node's direct relationships (Figure 4.5). *Dragging* a node is also related to clicking, but the students must hold down the left click and drag the mouse to rearrange the node's position in the DIME map. This allows students to reconstruct the orientation of the DIME map into a more personalizable visual display. *Deleting* nodes removes them from the DIME map along with their links with other nodes that share a direct relationship; students can click on the delete button (see Figure 4.6), click any nodes that need to be removed, and then press the "d" or "delete" key on the keyboard to remove them from the DIME map. Lastly, *hiding* nodes fades out the targeted node and its links, reducing cognitive load on the DIME map. Students and teachers used each of these features to create new and unique DIME maps (see Figure 4.8). Collectively, these features represent the total user interactions for each student, allowing them to personalize their DIME map. We analyzed the relationship between students' total number of user interactions with DIME and their pretest-posttest mean growth in self-efficacy for learning physics.

Figure 4.8

Customized DIME Map after a Student Deleted, Hid, and Rearranged Nodes



Note. Compare to Figure 4.7. Hidden nodes appear faded or with low opacity.

4.2.3. **Foundational Reflections on Students' Perceptions of DIME Maps**

The qualitative findings from a previous study influenced methodological decisions for the current study. In that 2018 pilot study, we analyzed interviews from students who interacted with DIME maps (Rugh, Capraro, & Capraro, 2021). There were originally five emergent themes: *pre-assimilator of knowledge*, *improved accessibility*, *high interactivity*, *tool for empowering learners*, and *initial complexity*. In designing the methods for the current study, we focused on three of those themes—DIME maps as highly interactive, as a tool for empowering learners, and as presenting initial complexity. Here, we further exemplify those themes by strategically integrating quotes with a thick description (see Denzin, 1989; Lincoln & Guba, 1985; Ponterotto, 2006) of the setting, explicating our understanding of how a participant's intent informed the work around each theme.

4.2.3.1. DIME Maps Provide High Interactivity

Students commented on the highly interactive nature of DIME maps and how it helped them to learn. This interactivity provided by DIME maps allowed students to overcome cognitive hurdles that they might not have with a static concept map. Students described that despite being a little confused, moving the map around helped them to understand the material. A triumph after persisting through struggle, this student experienced a mastery learning experience. Students using DIME maps appreciated "being able to highlight things and see where they are on the page," indicating their valuing the clicking and navigating features of the DIME map. According to CATLM, interactive elements in this educational technology enable students to actively engage in their learning and take ownership of their learning process (Moreno & Mayer, 2007). From this emergent theme, we decided to look at individual students' interactions with their DIME maps.

4.2.3.2. DIME Maps are a Tool for Empowering Learners

Students saw the DIME maps as an intelligent learning tool that improved their ability to learn. One day, while the students were working, the teacher asked them to explain angular momentum and how it related to the topics they had explored the day before. No constraints were given regarding where they could go for information. Some groups turned to Google. Others recalled prior encounters with "momentum" and tried to make guesses as to how it would work in a spinning object. Some groups instead immediately opened their DIME maps, identified the concept in the map either visually or with a quick search, and used the map to jump to the page where the concept was identified or to explore the relationships between concepts. One student commented, "Hearing things doesn't allow me to process things better. So knowing that I would be able to have these resources is really helpful." Pausing to think for a moment, the student summarized their feelings about the DIME maps, "It's almost as if, I know this sounds bizarre, but there's another teacher I guess. Because there's the textbook, but there's also the graph that moves." The student saw DIME maps as a sort of alternative to the textbook or to the teacher. In their view, the DIME map was reminiscent of an intelligent tutor—a system designed to model the process of learning. When the students observed the connections presented in their DIME maps, a vicarious learning opportunity arose. Viewing the connections modeled for students how to make their own connections between concepts and helped students to understand how the content was all connected. We (the research team) began to view DIME maps as this intelligent tutor, capable of providing experiences where students could feel more confident in their ability to learn and connect new knowledge by observing the system do it first.

Students commented that the DIME map made it easier to understand all of the concepts in the chapter were related to each other, thus increasing their self-efficacy in their ability to understand and learn physics. This deep interdependence of subjects and conceptual knowledge lies at the heart of assimilation theory and demonstrates how

DIME maps provided students with a vicarious opportunity to observe and internalize the connections. One student simply stated that DIME maps were "just a good platform to look at to enhance your learning." This quote further indicated that interactions with DIME maps helped students feel more empowered to learn. Thus, a further exploration of how students' engagement with DIME maps affects improvements in learning and self-efficacy towards learning was merited.

4.2.3.3. Students Using DIME Maps Encountered Initial Complexity

After engaging with DIME maps, students' comments were not all positive, particular regarding the visual complexity of the DIME map. All of the mathematically based concepts in the textbook chapter were represented at once as nodes, and their relationships as arrows between each node. Bombarded by this information, many students experienced high initial cognitive loads. Some students gave their candid opinions that DIME maps might just be too confusing or that there were too many objects presented on the page. Of course, we took this information to heart and made notes to alter the presentation of DIME maps in future versions in a way that would lower cognitive loads. Still, we found a redeeming trait when initially confused students described how "But once we moved [the map] around, I figured it out and I understood."

Eureka! From that statement, we realized that it is important to see how students persevere past their initial apprehension and engage with the DIME maps. It is important to allow learners the opportunity to struggle productively (Barlow et al, 2018; Murdoch et al., 2020). Some students used DIME maps only a little, and some used them throughout the week; but students who viewed the DIME maps longer may have moved past the initial high cognitive load to see DIME maps for the educational tool that it was meant to be. After persisting through initial difficulty and complexity, viewing DIME maps served as a vicarious learning experience that helped students visualize the connections between concepts. From this theme, we decided to look at user interactions and their correlation with the outcomes of interest.

In addition to these quotes, we observed that a majority of students were actively engaged with their DIME maps and even tried to figure out how it worked or discover software bugs to help improve the design of future versions of the technology. The themes gathered from interviews with students provided guidance for the quantitative analysis of the effectiveness of DIME maps in improving physics self-efficacy and gave promise to future iterations of DIME maps, as educational tools are only as good as the attitudes of the students using them.

4.3. Method

This study was guided by the following research question: What is the relationship between students' interactions with DIME maps and students' self-efficacy towards physics?

For this exploratory study, we used a single group pretest-posttest design. This quasi-experimental design is explained as a better attempt to control for extraneous variables that often remain uncontrolled by a lack of experimental design (see Shadish et al., 2002). We used the qualitative findings from our prior work (Rugh, Capraro, & Capraro, 2021) as a substantive or formative foundation to enrich the current quantitative design (Madey, 1982). For this study, we used a one-group pretest-posttest design to determine the effect of using DIME maps on students' self-efficacy in physics (the data are available from Barroso et al., 2019). Significant correlations indicated existence of potential relationships between interactions and self-efficacy growth.

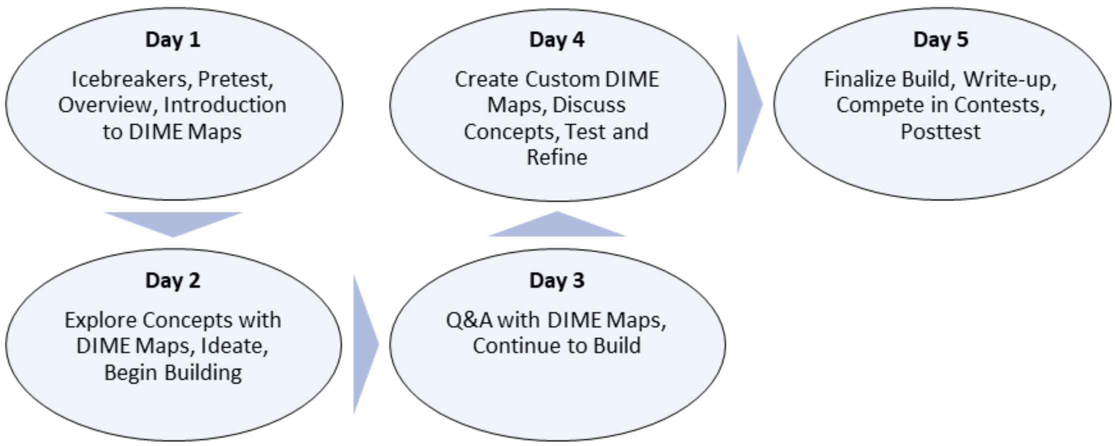
4.3.1. **Study Setting**

This study took place during the summer of 2019 at an informal STEM summer camp. Students (*n* = 15) were engaged in a project-based learning course that took place over a period of five days. During the PBL course, the teacher introduced the students to DIME maps and gave them individual access to create their own personal DIME maps from the college level physics textbook—an openly licensed PDF textbook available online (Wolfe et al., 2015). Using laptops, tablets, and cell phones, students could explore physics content information through the PDF textbook and associated DIME map. The students were encouraged, but not required, to use the provided DIME map throughout the study. However, the amount of interaction they had was not set for them. Rather, students were allowed to interact with the DIME map in their process of learning as the lessons progressed.

The summer 2019 pedagogy was centered around a STEM project-based learning course (STEM PBL; see Bicer & Lee, 2019; Capraro et al., 2013) and required that the students learn and apply knowledge of fixed-axis rotational motion as they built their own fidget spinner. The intervention began with the students taking a pretest on the first day of the STEM PBL course and ended when they took a posttest on the last day of the course. During this five-day study (for an overview, see Figure 4.9 or Rugh, Beyette, et al., 2021), students explored concepts using a DIME map and modified it to meet their individual needs throughout the course.

Figure 4.9

Study Day-by-Day Overview



4.3.2. **Participants**

There were originally 17 students who participated in the study. We excluded two students' responses from analysis because of pretest ceiling effects—they exhibited a perfect positive score on the self-efficacy survey. Perhaps larger scales should be considered for future studies in order to encourage students to select more moderate values that could change in measurable and meaningful ways. Students' grade levels ranged from 8 to 12 (Table 4.1), and their racial/ethnic identifications were as follows: 46.7% of the students were White, 20.0% were Hispanic (non-White), 20.0% were Asian, 6.7% were African American, and the remaining (6.7%) provided no specific race/ethnicity (Table 4.2).

Table 4.1

Grade Levels for the Students in this Study

Grade	*n*	Percent
8	1	6.7
10	7	46.7
11	4	26.7
12	3	20.0
Total	15	100.0

Table 4.2

Student Race/Ethnicity

Race/Ethnicity	*n*	Percent
Asian	3	20.0
African American	1	6.7
Hispanic	3	20.0
White (Non-Hispanic)	7	46.7
Other	1	6.7
Total	15	100.0

4.3.3. **Intervention**

Before the class began, the teacher uploaded the rotational motion chapter of a common university physics textbook into the DIME map system and obtained a DIME map for their students to use. Although the DIME map system can automatically generate a map, the teacher worked with a computer science team to select 19 mathematical physics concepts to focus on in the generated DIME map. Each student had access to their own DIME map via laptop, tablet, or cell phone. The students could use their DIME map at their discretion while exploring the physics involved in rotational motion.

4.3.4. **Instrument**

To measure students' self-efficacy in physics learning, we used a self-efficacy survey adapted from Klobas et al. (2007). The original survey was developed based on a self-efficacy scale used by Wood and Locke (1987) and research on self-efficacy scales such as "Bandura's guidelines for scale construction" (Klobas et al., 2007, p. 4; see also Bandura, 2006; Maurer & Pierce, 1998; Pajares et al., 2001). In the survey for the current study, students were asked to answer six questions on a scale from 0 to 10 about how well they can visualize, understand, learn, and remember key concepts in their physics classrooms (0 = *extremely low confidence* and 10 = *extremely high confidence*). Question 3 served as an anchor for question 4, which was intended to better discriminate the construct. A similar relationship existed between question 5 and question 6. The self-efficacy survey consisted of the following questions:

1. I am able to visualize ways in which physics concepts are related to each other.
2. I am able to learn difficult physics concepts.
3. Soon after science class is over, I am able to remember *most* of the key concepts.
4. Soon after science class is over, I am able to remember *all* of the key concepts.
5. I can understand *most* of the key concepts covered in my science classes
6. I can understand *all* of the key concepts covered in my science classes.

The original survey had high internal reliability ($\alpha = 0.91$; Klobas et al., 2007). The reliabilities for the data in hand in this study were similarly high for pretest (α = 0.90) and posttest ($\alpha = 0.93$) scores. For each of the questions on the survey, we tested the correlation between mean difference (growth) and the number of user interactions with the DIME map.

4.4. Results

In this study, we examined the relationship between user interactions with the DIME maps and those users' growth in self-efficacy. Pairwise correlation between DIME map user interactions and mean growth are reported.

4.4.1. **User Interaction Data**

Each of the user interactions were treated equally (1:1) in this study and were tested for correlations with the growth in self-efficacy questions from the pretest-posttest survey. After the previous study (Beyette et al., 2019), we upgraded the DIME Map system with visual enhancements, system optimizations, and improvements to the DIME map user interactions. Some students preferred specific DIME map user interactions over others, such as searching or clicking, while others used a mix of every user interaction. We examined each students' total user interactions with their DIME map (Figure 4.10) as well as a breakdown of each individual student's interactions (i.e., search, click/drag, delete, and hide; Table 4.3). "Search" is the total number of search interactions per student, counting every keystroke. "Click/Drag" is the total number of nodes clicked and/or dragged per student. "Delete" is the total number of nodes deleted per student. Finally, "Hide" is the total number of nodes hidden per student.

Figure 4.10

Total User Interactions per Student

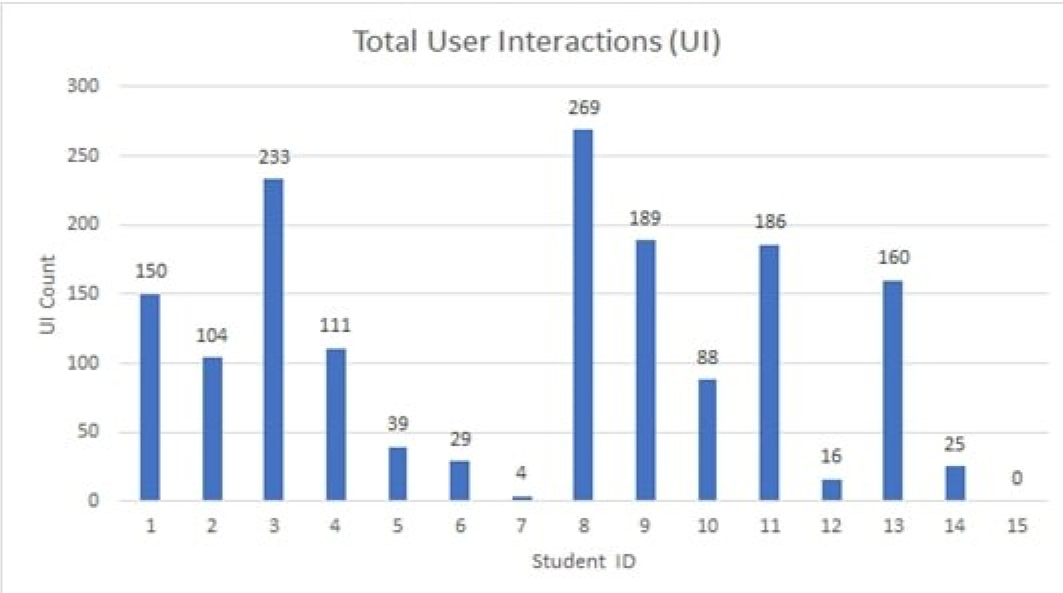


Table 4.3

Breakdown of User Interactions with DIME Map per Student

Student ID	Search	Click/Drag	Delete	Hide
1	92	50	0	8
2	0	86	18	0
3	81	138	14	0
4	87	24	0	0
5	16	23	0	0
6	0	25	0	4
7	0	4	0	0
8	195	64	10	0
9	29	136	10	14
10	49	29	10	0
11	0	176	10	0
12	7	9	0	0
13	80	78	2	0
14	16	9	0	0
15	0	0	0	0

The most used interaction was clicking/dragging, followed by searching, deletion, and hiding (see Table 4.3). The clicking and dragging feature has two uses: to navigate to the place the concept was first defined or to rearrange the DIME map by dragging the clicked node to a new destination. Numbers related to clicking and dragging may be inflated due to students playing around with the DIME map instead of focusing on a specific learning objective. For example, a student using the search feature is more likely to be searching with specific words related to their current learning objective rather than aimlessly manipulating the DIME map. More studies are needed in order to understand the learning behaviors of each student and their relation to each DIME map user interaction.

4.4.2. **Self-efficacy Mean Growth and Pairwise Correlations**

To answer our research question, we hypothesized that the total number of user interactions with the DIME map would have a statistically significant positive correlation with self-efficacy as measured by the self-efficacy scale. To test the hypothesis, correlation coefficients and statistical significance were found using StataIC 16. We calculated total user interactions and mean *Growth*, or change-from-baseline score, between pretest and posttest results (see Table 4.4). We then investigated statistically significant ($p < .05$) inter-item correlations for the survey and correlations between individual questions and the total user interactions with the DIME map (see Table 4.5). We summed Q1, Q2, Q4, and Q6 to generate *Self-efficacy* (*SE*) *Growth Total*

Table 4.4

Mean and Standard Deviation for the Students' Pretest-Posttest Results

	Mean	Standard Deviation
Q1 Growth	1.000	2.138
Q2 Growth	0.800	2.007
Q3 Growth	0.133	2.066
Q4 Growth	0.200	2.145
Q5 Growth	-0.867	1.356
Q6 Growth	-0.600	2.898
SE Growth Total*	1.400	5.755
Total User Interactions	106.867	87.790

Note. We summed growth on Q1, Q2, Q4, and Q6 to generate *SE Growth Total*

Table 4.5

Correlations with Total User Interactions

	Total UI
Total UI	1.0000
Q1 Growth	0.3722
Q2 Growth	0.3728
Q3 Growth	*0.5791
Q4 Growth	*0.5286
Q5 Growth	*0.6729
Q6 Growth	0.2725
SE Growth Total	*0.6026

Note. Asterisk (*) indicates statistically significant correlation coefficient at ($p < 0.05$).

Students' total number of user interactions with DIME maps was positively correlated with growth on questions 3, 4, and 5 ($p < 0.05$). Students' self-efficacy in their ability to remember *most* (question 3) or *all* (question 4) of the key concepts had statistically significant ($p < .05$) positive correlations with their total number of interactions with DIME maps. Students' self-efficacy in their ability to understand *most* (question 5) of the key concepts after attending science class was also positively correlated with their total user interactions. Therefore, we generally can claim that students who interacted more with the DIME map also gained more in self-efficacy, at least with respect to those three questions. However, due to the limitations of our study, further investigations into the use of DIME maps is merited.

4.5. Summary

DIME maps provided a modern twist to the static graphic organizer. Students found it helpful navigating the textbook and for helping to reduce the cognitive load for learning the physics concepts being presented. Self-efficacy was also improved through the use of DIME maps.

4.5.1. **Limitations**

There are a few limitations and questions concerning this study that can help guide future studies and development of DIME maps. First, the group was an intact voluntary informal STEM camp; therefore, there may have been significant self-selection bias. In most cases, the child selected to participate in the camp. In some cases, the parent or parents alone may have selected for the child to attend the camp. This presents a conundrum: if the child selected, then he or she was more likely to make the best of the learning experience; however, if a parent selected, an entirely different possible scenario could have played out. In this case, the child could have become rebellious and done little work to gain from the experience. This may not be common, however, as research seems to indicate that parents' support of and interest in their child's academic experiences have a positive influence on both achievement and commitment (Aschbacher et al., 2010). It would be helpful for a future study to recruit participants from a much larger group that might be more representative of the general population.

Another limitation may lie within the wording of the first item of the survey given to participants. The first item on the survey states, “I am able to visualize ways in which physics concepts are related to each other.” Although this question may appear to test for self-efficacy in learning, it actually refers to self-efficacy in the ability to visualize relationships between concepts. DIME maps transform the mathematical objects and declarations in linear PDF textbooks into interactive concepts maps, potentially removing extra cognitive load by making the relationships explicit and multi-dimensional. Theoretically, for their learning to be meaningful, the students have to make connections between new learning and their own knowledge structures. DIME maps allow students to *understand* how everything is *interconnected* but may not help students *visualize* how physics concepts are related. However, it would not be unreasonable to believe that students may be able to better visualize connections as they see more and more concept maps. Afterall, students who spend longer with concept maps experience larger benefits than students learning through traditional methods (Schroeder et al., 2018). When students encounter traditional textbooks after engaging with DIME maps, their minds may automatically begin arranging the knowledge with relationships and connections reminiscent of DIME maps. Therefore, future works should examine the effects of longer meaningful interactions with DIME maps.

4.5.2. **Future Works**

Based on the results of this study, future iterations of DIME maps will be designed to further assist online learning for students and teachers. Teachers will be able to directly manipulate the pages and concepts used to build DIME maps for their students, allowing them to mirror the content in their classroom, such as a lecture, exam, review, or homework assignment. Secondly, teachers will also be able to analyze the individual user interactions, allowing them to identify possible learning struggles or interests in the classroom. Furthermore, having students interact with and create concept maps can be used as a meaningful assessment of students' conceptual knowledge (Hartmeyer et al., 2018; Walker & King, 2003; Watson et al., 2016). DIME maps have the potential to provide a powerful assessment of knowledge and learning by automatically assessing the difference between two DIME maps and analyzing how students progressed with their DIME maps over time. Another feature that makes DIME maps a potentially powerful online learning tool is that they allow students to automatically generate searches using popular search engines such as Google; a feature which has been studied as a valuable addition to modern concept maps (Leake et al., 2004). In addition, students will be able to collaborate with each other by sharing, liking (voting), and collaborating on DIME maps, enhancing both personalized learning and collaborative learning—an outcome expected from prior research on concept maps (Nesbit & Adesope, 2006; Schroeder et al., 2018). Overall, the DIME map will become a powerful learning partner for each student as they design and interact with more DIME maps in current and future courses, both online and in person.

Although the findings from this study were based on a single week-long intervention, longer interactions with DIME maps could prove to be beneficial. Through a comprehensive meta-analysis, learning while using concept maps for one- to four-week interventions has been shown to be more effective than for interventions lasting less than a week (Schroeder et al., 2018). This suggests that the benefit of DIME maps found in this study might be even greater if students had more time to learn how to use and interpret DIME maps and explore additional content using them. Additionally, when students understand how to make concept maps, they are more successful at using concept maps to improve their learning (Novak, 1990). Future studies should investigate the effects of using DIME maps for longer periods of time and begin with an introduction to making concept maps.

4.5.3. **Student Accessibility to Computers**

Accessibility to laptop or desktop computers continues to increase at home and in public schools for students in the United States, allowing for the integration of new technology in classrooms. According to the National Center for Education Statistics (NCES; 2018), overall use of computers in the year of 2015 for children ages 3 to 18 was 94%, and 96% of schools in 2016 met the Federal Communication Commission's bandwidth requirements (National Science Board, 2018). In addition, since the announcement of the United States Federal Government Initiative ConnectED, the percentage of schools with instructional computers increased to 100 percent and the number of laptop computers on carts and in classrooms ranged from 58%–69% for all public schools (NCES, 2008, Table 1 & Table 2). This laid the groundwork for the integration of computers in classrooms for educational software. This increase in computer availability and internet access means that DIME maps can function as a widely available and accessible learning tool for classrooms across the United States.

4.5.4. **Conclusion**

Creating new pedagogical strategies to improve self-efficacy and understanding of important concepts in physics-based classrooms continues to be a complex and difficult task. However, with the help of DIME maps, traditional resources such as textbook and lecture notes are automatically transformed into dynamic concept maps, providing new representations of knowledge that improve self-efficacy and understanding of important physics concepts. With DIME maps, teachers and students can interact with dynamic concept maps whose transformation of knowledge adapts to their user interactions and feedback. This allows DIME maps to be malleable to any new or current teaching system and methodologies in subjects involving mathematics, as DIME maps extract and transform the raw mathematical language found in traditional textbooks or lecture notes into a non-linear dynamic and adaptive concept map. Results show that users who interacted with the DIME map saw an increase in self-efficacy regarding their abilities to understand and remember most of the key physics concepts in a science class. This key finding aligns with research and theories on interactive learning environments that suggest meaningful learning occurs when students spend conscious effort to select, organize, and integrate new information with prior knowledge structures (Moreno & Mayer, 2007). Future explorations and developments with DIME maps may reveal further insights into interactive educational learning environments.

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5. BREAKING BARRIERS FOR STEM LEARNING: A META-ANALYSIS OF THREE YEARS OF FINDINGS ON DIME MAPS

5.1. Introduction

Textbooks present knowledge linearly, with one large section of expository text after another, which can cause readers to struggle with understanding new concepts. This linear representation of knowledge is contradictory to the internal representation of knowledge in our minds (Kalyuga, 2006; Tian et al., 2020). Our internal representations of knowledge are foundational to and a basic aspect of our ability to understand the world around us (Phillips et al., 2020) and are better represented as a web of interconnected ideas with a complex organization and structure (Hiebert & Carpenter, 1992; Hiebert & Lefevre, 1986; Saxe et al., 2013; Stelzer et al., 2009; Sweller, 1988;). Despite the conflict between internal representations of knowledge and what students are presented in textbooks, students are often required to memorize information, processes, and formulas (see Hamzi et al., 2021; Nicoara et al., 2020; Srivastava et al., 2020). This can lead to poor study practices, such as rote memorization, where students attempt to memorize formulas, concepts, and ideas as independent and distinct pieces of information. Unfortunately, rote memorization alone has been found to be ineffective for long-term retention (Byers & Erlwanger, 1985; Cai & Wang, 2010). Many students struggle with achieving meaningful learning when reading traditional textbooks and other author-centric linear representations of knowledge because the connections between concepts, equations, expressions, and formulas are hidden (Tian et al., 2020). Therefore, researchers continue to improve and adjust textbooks (Andersen, 2020; Rohrer et al., 2020; Wan & Lee, 2021). Although textbooks are unlikely to disappear from the classroom setting, educational technologies can provide support to engage students in meaningful learning and retention through nonlinear representations of knowledge. We built this study on the foundation of two influential and overlapping educational theories to present and examine the effects of using an educational technology designed to assist in meaningful learning from textbooks.

The first component of the theoretical foundation for this study is *assimilation theory*, also known as Ausubel's (1968) Assimilation Theory of Meaningful Learning. Assimilation theory can provide valuable insights into how students learn and retain meaningful knowledge (Tian et al., 2020). In contrast to the linear representation of knowledge in many textbooks, assimilation theory posits that learning is best achieved by anchoring new knowledge into existing internal knowledge structures containing prior knowledge and the relationships among the prior knowledge. This is the theory that led Ausubel to famously state, "If I had to reduce all of educational psychology to just one principle, I would say this: The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly" (Ausubel, 1968, epigraph). If students are enabled to and choose to integrate new concepts and prepositions with their existing knowledge, meaningful learning can occur (Novak, 1998). In other words, dynamic and adaptive non-linear transformations of knowledge facilitate learning, as the human mind requires new and prior knowledge to be linked together under assimilation theory.

Complementing assimilation theory, the *cognitive-affective theory of learning with media* (CATLM) is the second component of the theoretical underpinnings for this work. This learning theory is based on seven assumptions about cognitive and affective processes within multimedia learning and presents guiding principles for design elements that would lead to positive student outcomes (Moreno & Mayer, 2007; Park et al., 2014. The cognitive theory of multimedia learning (CTML; Mayer, 2005) served as a foundation for the development of CATLM, which expanded on the assumptions and principles of CTML in order to encompass interactive, multimodal learning environments (Moreno & Mayer, 2007). As such, CATLM provides the perfect lens to view this study of an interactive multimodal educational technology. According to CATLM, learning in multimodal environments can be supported by five types of interactivity:

- *Dialoguing*—the learner can ask a question or provide input and receive feedback or output.
- *Controlling*—the learner can set the pace or order of learning.
- *Manipulating*—the learner can set parameters, zoom in or out, or move objects on the screen to aid in understanding.
- *Searching*—the learner can input a query and find new content within or beyond the environment being explored.

- *Navigating*—the learner can navigate to different content areas within the environment.

Viewed through the lens of CATML, learners utilize these types of interactivity through self-regulated learning to create meaningful internal knowledge representations. This process is tied to one of the key assumptions of CATLM—how students must select relevant verbal and non-verbal information from learning media and integrate them (or assimilate them) into prior knowledge structures (Moreno & Mayer, 2007)—and directly relates to assimilation theory and assumptions about how learning occurs. One of the key goals for interactive educational technologies, under CATLM, is to help learners make connections to prior knowledge. In this way, CATLM explains how the educational technology in the current study has potential value for students because the technology engages students in all five types of interactivity and requires them to select information to be assimilated into their own existing knowledge structures.

Recently, technologically enhanced animated or interactive concept maps have been introduced to further help improve learning (Akpinar & Ergin, 2008; Atas, 2019; Schroeder et al., 2018). However, recent findings have led researchers to suggest that more research is needed to further understand where such augmented concept maps may be employed for positive benefits to students (Schroeder et al., 2018). For this study, we meta-analytically examined the past three years of data regarding use of the automatically generated interactive concept maps known as Dynamic and Interactive Mathematical Expressions (DIME) maps according to the following research question:

What effect has using DIME maps had on cognitive and affective learning outcomes for students?

5.2. Literature Review

A large corpus of research was reviewed to develop DIME maps and the perspective with which we view our results. First, DIME maps were developed to be visually similar to concept maps; therefore, we present prior research on concept maps as highly relevant and potentially applicable to DIME maps. Next, we describe exactly what DIME maps are and how they are quickly and automatically created from Portable Document Format (PDF) textbook chapters that a teacher or student uploads. Third, we describe the interactive features of DIME maps and how they align with prior literature on CATLM and types of interactivity. Finally, we tie together the learning theories and prior literature to support the development and testing of DIME maps.

5.2.1. **Concept Mapping and Cognitive and Affective Outcomes**

Concept maps are one way in which students can engage with dynamic and adaptive learning and non-linear representations of knowledge. Through meta-analytic methods, using concept maps has been shown to be significantly more effective at improving cognitive and affective learning outcomes for students than alternative treatments, such as discussions, lectures, studied or constructed lists, outlines, and text (Schroeder et al., 2018). Similar positive effects have been found for several decades through systematic reviews and collections of research on concept mapping (Adesope &

Nesbit, 2010; Hartmeyer et al., 2018; Horton et al., 1993; Mihai et al., 2017; Nesbit & Adesope, 2006; Novak, 1990; Yue et al., 2017).

When students rely only on reviewing strategies as a form of memorization, information is typically stored as disparate pieces of knowledge in long-term memory, making it difficult to draw connections between ideas and develop conceptual understanding (Bransford et al., 1999). In contrast, graphic organizers, such as concept maps, enable students to visualize connections between prior knowledge and new learning (Hill, 2005; Lopez et al., 2013; Novak, 1998). Concept mapping has been shown to have positive effects on long-term memorization (Nicoara et al., 2020). By demonstrating the connections between concepts, concept maps reduce the cognitive load required to process new knowledge (Hill, 2005; Novak, 1998; Stull & Mayer, 2007). Therefore, using concept maps has the potential to improve cognitive gains in students.

The affective construct we examine in this study is self-efficacy in physics. The findings about the effects of concept mapping on students' academic self-efficacy is not as conclusive as for cognitive outcomes. Several researchers found that concept mapping improves academic self-efficacy (Adiyiah et al., 2020; Chularut & DeBacker, 2004; Roshanger et al., 2020). However, there is inconsistency among the comparison groups of studies on concept mapping, with one study finding positive impacts of concept mapping on self-efficacy when compared to an independent study control group (Chularut & DeBacker, 2004), one study indicating that concept mapping groups did not perform significantly better than their comparison groups who received similar high-quality instruction strategies (Roshanger et al., 2020), and one study not making any comparisons to a control group (Chularut & DeBacker, 2004). It is amidst this inconclusiveness that we hope to test whether DIME maps also have a positive impact on affective growth as measured by self-efficacy survey questions.

Unfortunately, concept maps require a significant amount of time to prepare, especially if there are many concepts to connect (Brownson et al., 2012; Roshanger et al., 2020; Vaughn et al., 2017). Interactive concept maps take even more effort to create. Addressing these challenges, we created the DIME Map system to automatically parse PDF text and produce a fully functioning interactive map (a.k.a. a DIME map) of the mathematically based concepts contained in that PDF text.

5.2.2. **Dynamic and Interactive Mathematical Expressions (DIME) maps**

At first glance, DIME maps appear similar to concept maps that preemptively connect the mathematical knowledge contained in a PDF document. However, a few unique differences set DIME maps, a dynamic digital graphic organizer, apart: they are automatically generated, they allow the user to focus the map on their own personal and individual learning needs, and they can be used to physically navigate the PDF document by clicking on nodes. As with concept maps, DIME maps have the potential to reduce cognitive load (if carefully implemented), to provide multiple representations of knowledge, and to help students visualize connections between prior knowledge and new knowledge. The DIME Map system is a software that creates DIME maps (such as in Figure 5.1) by analyzing a document (such as in Figure 5.2), extracting mathematical knowledge, connecting related concepts, and representing that knowledge through an interactive and personally customizable manipulated depiction (Rugh et al., 2019; Beyette et al., 2019). The unique properties of DIME maps make them ideally situated to address the concerns about the time and effort needed by educators to create effective concept maps. The DIME Map system is a powerful learning tool due to the way it identifies important text within PDF documents (i.e., textbooks), specifically mathematical objects.

Figure 5.1

Section of a DIME Map Produced from a Physics PDF textbook

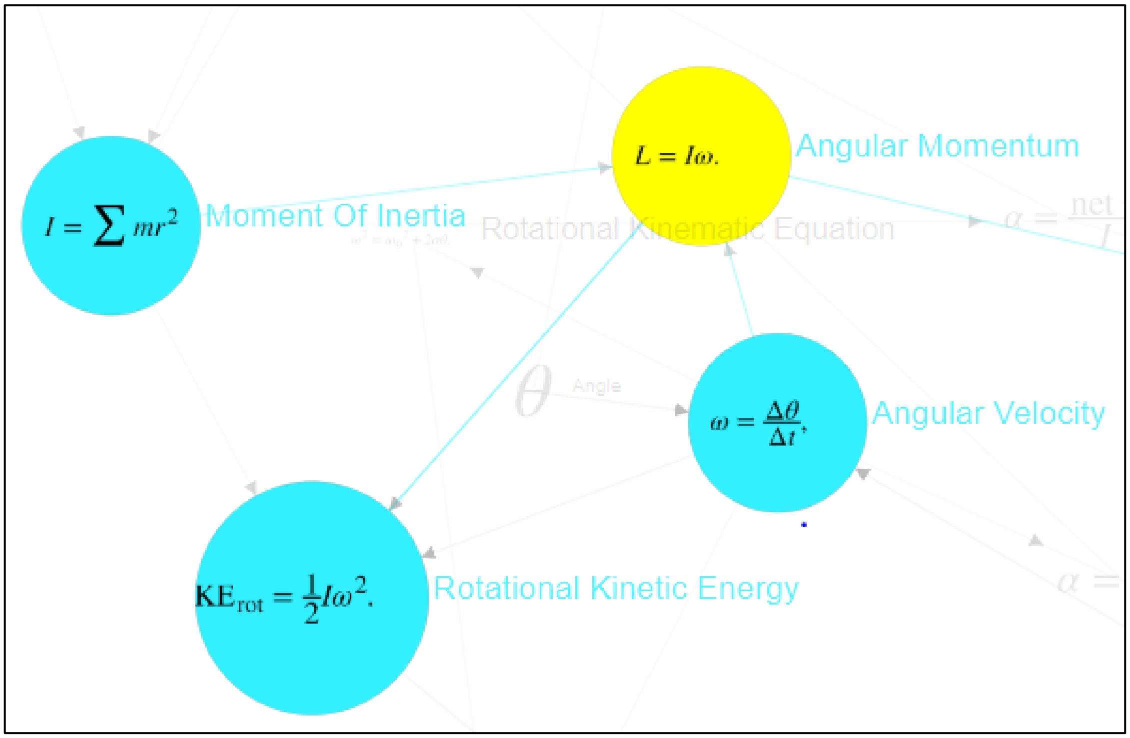


Figure 5.2

Section of PDF Textbook Used by the DIME Map System to Produce the DIME Map Presented in Figure 5.1

Why does Earth keep on spinning? What started it spinning to begin with? And how does an ice skater manage to spin faster and faster simply by pulling her arms in? Why does she not have to exert a torque to spin faster? Questions like these have answers based in angular momentum, the rotational analog to linear momentum.

By now the pattern is clear—every rotational phenomenon has a direct translational analog. It seems quite reasonable, then, to define **angular momentum** L as

$$L = I\omega. \qquad (10.90)$$

This equation is an analog to the definition of linear momentum as $p = mv$. Units for linear momentum are $\mathrm{kg} \cdot \mathrm{m/s}$ while

We define *mathematical objects* as a collection of characters that may represent a mathematical variable, expression, equation, or formula whose *semantics* (i.e., object meanings, order of operations, and logical syntax) are used to generate the corresponding LaTeX form. The automatic recognition of mathematical objects has been researched since 1968 (Anderson, 1968), and it continues to be a difficult challenge in the content analysis community. An extensive review of the history of different methods used to extract and reconstruct mathematical objects in images and PDF documents can be found in the dissertation by Théodore Bluche (2010). Current state-of-the-art mathematical object and declaration extraction was developed through prior collaboration between Aggie STEM and the Real Time Distributed Systems computer science and engineering lab at Texas A&M University (see Wang et al., 2019). The DIME Map system synthesizes decades of research into the automated recognition of mathematical objects.

After identifying mathematical objects in the PDF text and their corresponding semantics, the DIME Map system then identifies declarations. *Declarations* represent word meanings and word relations for each mathematical object, such as a name, identifier, or definition. Collectively, the mathematical objects, semantics, and declarations that are automatically extracted from the PDF document make up the core features of the DIME map. Once extracted, the mathematical objects and their associated declarations are arranged in an organized manner with links connecting related mathematical objects. The result is a dynamic and interactive digital map or web showing the interrelationships between the mathematical content of a given PDF document.

Mathematical objects are prevalent in physics textbooks and contain different attributes than expository text. For example, mathematical objects differ from natural language in that they are often presented in different font sizes and include Unicode, bounding boxes, and glyph names. The DIME Map system extracts these raw attributes from the PDF document using Apache PDFBox software (2019). Afterwards, each symbol (individual characters) is classified as either a mathematical object or expository text using a likelihood ratio test model based on the font size, font type, and glyph name parsed by PDFBox. Each symbol is merged with its neighboring symbols if they are within a specific gap threshold, creating a token (set of symbols) that could represent an inline or display-line mathematical object. Heuristic rules that utilize mathematical syntax and universal symbols, such as the equality operator, are used to merge expressions and formulas that otherwise might be outside the gap threshold due to spacing or formatting issues. The resulting tokens are classified as mathematical objects (Wang et al., 2019) and represent a major component in the core features used to build the DIME Map system's feature network (Beyette et al., 2019). The next step conducted by the DIME Map system is then to represent these mathematical objects in a meaningful way for students.

Knowledge transformation is achieved through natural language processing machine learning techniques, including calibration, anchoring, mapping across, Bayesian

Network classifiers, and maximum entropy classifiers. Each token that is identified as a mathematical object and its associated declaration, which is determined from natural language used in the PDF textbook, is recovered through a majority vote, or ensemble classifier, achieved through naive Bayesian classifiers using these three features: distance, word stem, and part-of-speech tagging (Lin et al., 2019). Each feature is used to create a likelihood assertion that a mathematical object is associated with a particular declaration based on the assumption that it satisfies a conditional independence probability distribution. Laplace smoothing is used to estimate the probability of each feature based on negative (0) or positive (1) assertions of mathematical object declarations, which resolves the issue of an unknown feature causing a zero-probability estimation. Lastly, an ensemble classifier is used for determining if a mathematical object contains a labeled declaration, as the spatial, semantic, and syntactic properties are assumed to be independent features that complement one another. Labeled declarations make up the last component of the DIME Map system's core features and are used to build a DIME map, providing interactive features to users.

5.2.3. **User Interactions in DIME Maps and Interactivity Types**

The DIME Map system's core features represent information that is automatically recovered from the textbook, which is used to build a DIME map ready for use by students. Additional interaction features are used to allow the map to become dynamic and adapt to each individual user's learning and interaction behaviors. User interaction features represent how students can interact with the DIME map and PDF textbook through *clicking* (to focus), *clicking* (to navigate), *modifying and view controls*, *searching and double-clicking*. Finally, when DIME maps are presented to students, there are options to view different “levels” or complexities of maps (see Figure 5.3, Figure 5.4). The base level map shows only the simplest terms (e.g., “mass,” “distance,” and “time”) as well as the concepts that build from those foundational terms (e.g., “velocity”). The second level map shows concepts that build directly from the composite concepts in the first level (e.g., “acceleration” or “kinetic energy”).

An example of a portion of a DIME map can be seen in Figure 5.1. The yellow circle, $L = I\,\omega$, represents the mathematical objects the user has interacted with by left clicking on the circle labeled “Angular Momentum.” To reduce cognitive load, the DIME map focuses on the mathematical objects that directly build into or out of the focused yellow circle by marking them with blue circles. Because the map is essentially answering the questions, “What concepts build into this concept?” and “What concepts are built upon this concept?,” *clicking* represents the student interacting with the system under the *dialoguing* type of interactivity (Moreno & Mayer, 2007). Clicking on a node also navigates the adjacent PDF textbook to the location where that concept was first introduced; this additionally corresponds with the *navigating* type of interactivity. Finally, the clicking feature and the ability of users to choose what level of map they want to view corresponds with the *controlling* type of interactivity, where learners can control the pace or order of learning.

Figure 5.3

An Example of a Level 1 DIME Map Produced from a Textbook Chapter

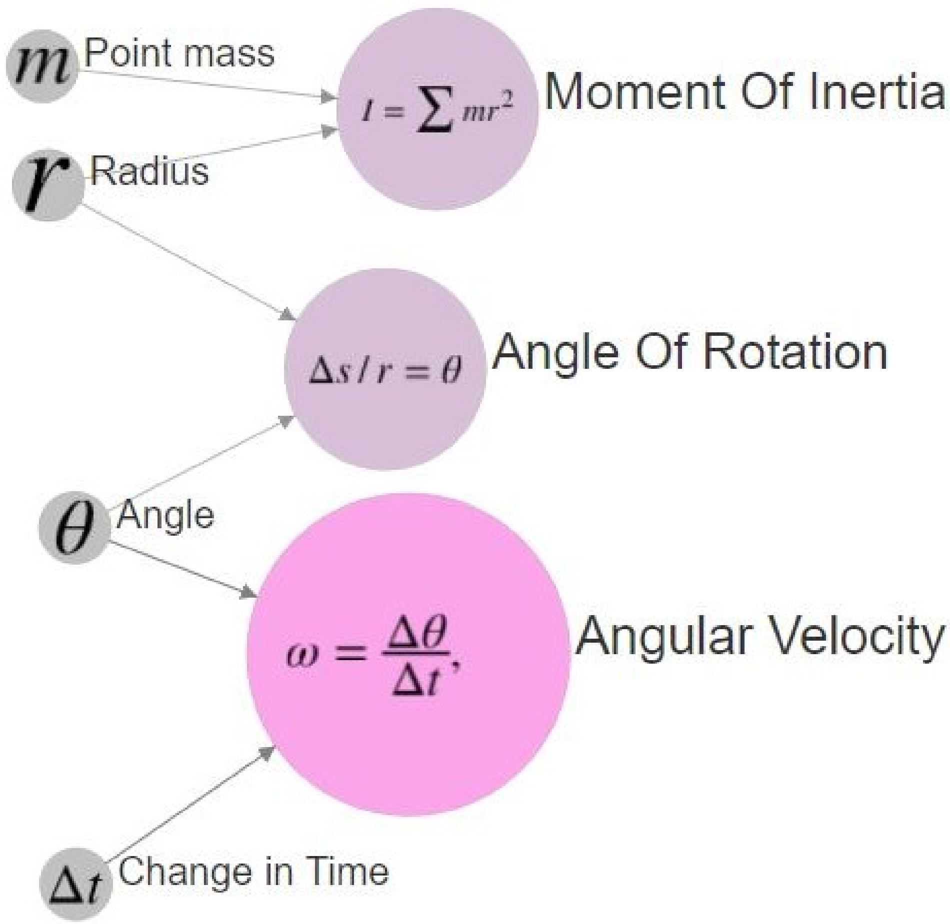
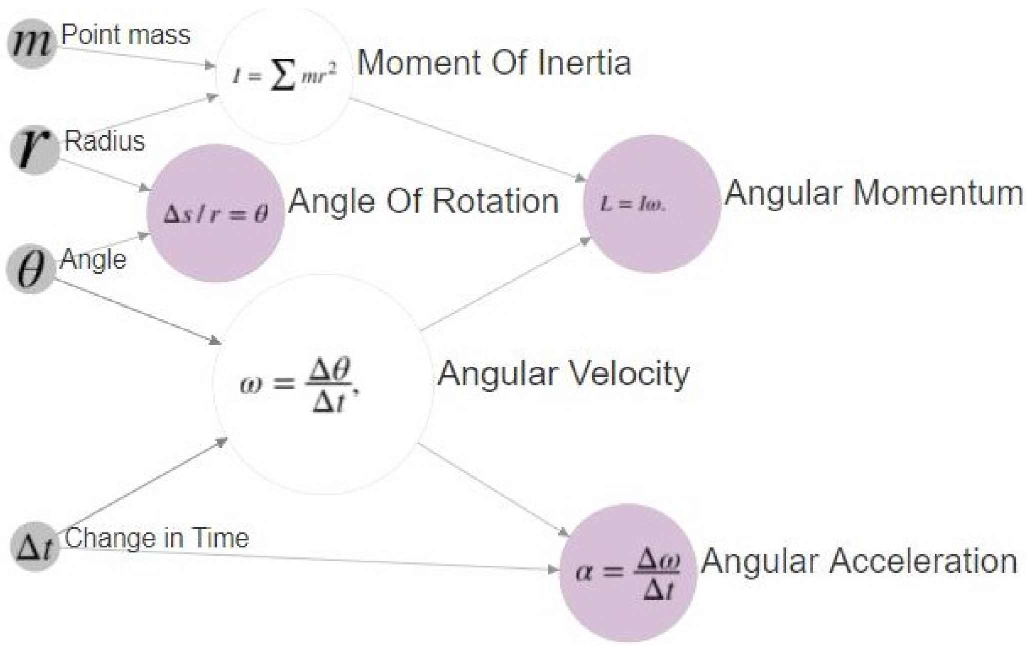


Figure 5.4

An Example of a Level 2 DIME Map Produced from a Textbook Chapter



The second interaction feature of DIME maps, *modifying*, refers to how users can manually modify their DIME map through dragging, deleting, adding, or hiding mathematical objects, thereby creating their own unique interpretation of the material. Users can use the *view controls* to zoom in or out on the map to display more or less detail or focus on specific content. These modifying features and view controls in DIME maps correspond with the *manipulating* type of interactivity (Moreno & Mayer, 2007).

The *searching* type of interactivity can be found in the third and fourth interaction features. Users can type plain text or variable names in the search bar (e.g., “angular momentum” or “theta”). Any node that contains a reference to those words or phrases will highlight on the map. This form of searching will look within the DIME map, but users can explore concepts outside of the DIME map as well. To do this, the user can *double-click* on a concept. Doing so will open a new browser window and search for that concept on Google. In this way, the map allows students to pursue additional content information not contained in the textbook or map itself.

With these capabilities, the DIME map serves as a powerful interactive tool for student learning. DIME maps provide a dynamic graphical representation of interrelated mathematical objects that allow the user to navigate the textbook and interact with the structure of knowledge in ways they never have before.

5.2.4. **Improving Cognitive and Affective Outcomes Using DIME Maps**

Because DIME maps are visually similar to concept maps and are highly interactive, they have the potential to improve cognitive and affective outcomes for students. Concept maps and DIME maps look similar and at a basic level present graphical representations of the connections between concepts. Both are built on a foundation of assimilation theory where they aim to help students make meaningful connections between prior knowledge and concepts currently being learned. Concept maps have proven to be effective at improving both cognitive and affective outcomes (Schroeder et al., 2018), and so we have reason to hypothesize that DIME maps may as well. Additionally, unlike traditional concept maps, DIME maps are highly interactive, containing all five types of interactivity described in CATLM (Moreno & Mayer, 2007). DIME maps have the potential to present complex conceptual information in a visually appealing way using features that can motivate learners to engage in meaningful assimilation of new knowledge (Mayer, 2014), thereby improving cognitive outcomes. Using interactive concept maps have also been associated with higher cognitive and affective gains compared to traditional methods of teaching and learning (Schroeder et al., 2018). Thus, we propose that the interactive nature of DIME maps (according to CATLM) and the graphic organization and representation of knowledge presented in DIME maps (according to assimilation theory) may contribute to improving students' cognitive and affective outcomes.

5.3. Method

To answer the research question, we conducted a meta-analysis on existing data regarding DIME maps and students' outcomes in terms of affective and cognitive measures. Just to ensure that we had all of the potentially applicable data regarding DIME maps, on September 8, 2021, we searched Web of Science, ERIC, Academic Search Ultimate, and APA PsychInfo for the phrases "DIME map*" or "mathematical expression* map." As expected with such a new technology, only a few (n = 5) results were returned. Eliminating duplicates brought the number down to three (i.e., Beyette et al., 2019; Rugh et al., 2019; Rugh et al., 2020). All three results were written by our team and discussed early implementations of DIME maps, but only one of the three explicitly provided quantitative data. Therefore, we retrieved the original data sets (n = 3) from three investigations into the effects of using DIME maps. As far as we know, at the time of this report no other data had been collected regarding the usage of DIME maps and the outcome variables of interest.

Two graduate students and two faculty members independently reviewed the data from these three reports to determine whether they could be included in a meta-analysis. They ensured there was adequate data to identify group means and standard deviations, effect sizes, and standard error of those effect sizes. The data were confirmed with their original sources. Results of interest were data relating to students' self-efficacy (affective) growth and knowledge (cognitive) growth. All three reports had data pertaining to these two outcome constructs. Other variables sought included participant demographic data, funding sources, and participants' prior knowledge in mathematics and science.

5.3.1. **Outcomes of Interest**

Students' cognitive outcomes were measured by a variety of instruments among the studies, including common quiz or test questions, asking the students to define concepts, and testing for recognition and recall of conceptual and procedural knowledge in physics. Within the affective domain, we decided to focus on self-efficacy in physics, as it was the most prevalent affective component tested for in all three studies and identified in the literature (Adiyiah et al., 2020; Chularut & DeBacker, 2004; Roshanger et al., 2020). The cognitive and affective growth were examined separately in two meta-analyses of the data.

5.3.2. **Measurement Devices**

The authors of the 2018 study created their own survey to measure affective and cognitive outcomes (see Appendix A, B, D, E, F and G). One affective question (2018a4) related to the students' enjoyment of physics rather than their perceived ability and was therefore removed prior to analysis. The items in the 2019 study designed to measure self-efficacy were adapted from Klobas et al. (2007) (see Appendix D). Two items (2019a3 and 2019a5) were used as anchors to improve the discriminating power of the following questions (see Klobas et al., 2007; Wood & Locke, 1987); those two items were not intended to be included in any analysis and were subsequently removed. The affective items in the 2020 study (see Appendix F) were adapted from Mahoney's (2010) survey, which originally was developed as an instrument for measuring students' attitudes toward STEM in high school STEM-based programs. Overall reliabilities for each construct within each study were acceptable considering the relatively well-defined construct of self-efficacy and the broad and complex nature of knowledge and understanding in physics (see Table 5.1).

Table 5.1

Reliabilities of Posttest Surveys: One Cognitive and One Affective Set from Each Year

	Cronbach's Alpha	
	Affective Questions	Cognitive Questions
2018	0.8348	0.4286
2019	0.8818	0.7371
2020	0.9176	0.5101

5.3.3. **Participants**

The final sample analyzed consisted of 75 students for affective outcomes and 72 students for cognitive outcomes. Their demographic information and breakdown by study can be found in Tables 5.2 and 5.3. The number of students in the final sample was less than the original number of students in the three studies (*N* = 94). There were originally 31 students in the 2018 study, 34 students in the 2019 study, and 29 students in the 2020 study. Those students were randomly assigned to either the treatment or the control groups. In 2019, however, three students were unable to get DIME maps working adequately on their devices, had four or fewer total user interactions with the DIME map system when the average number of interactions with the system by the students was 106, and were subsequently removed from this analysis. Two additional students were removed from the analysis because they left the posttest blank. Finally, one student's posttest was unreadable and could not be graded and was removed from the analysis as well.

The 2020 study also posed issues. Following the outbreak of COVID-19, the summer camp in which the 2020 study data was collected was held virtually via Zoom. The students were sent pretests before the first day of class and posttests after the last day of class. Only 16 students filled out the affective pretest and posttest, and only 13 students filled out the cognitive pretest and posttest—equivalent to response rates of 55% and 45%, respectively. For comparison, the 2018 and 2019 studies both had a 100% response rate. In the 2020 study data, one student in the control group had their affective scores removed from the analysis to avoid the ceiling effect because they answered every question at the maximum value on the pretest. One student in the treatment group had their affective scores removed because they gave opposite conflicting answers on a recoded item, answering that they strongly disagreed with statements 1, 2, and 3 in the 2020 Affective Survey (see Appendix F). Because of the smaller sample size of (and higher variation within) the 2020 setting, a lower weight was given to that study in the analysis.

Table 5.2

Final Sample Sizes and Participant Demographics

Group	*n*	Female	Male	Asian	Black or African American	Hispanic or Latino	White (non-Hispanic)	Other
2018 Total	31	10	21	0	0	9	22	0
Treatment	16	5	11	0	0	5	9	0
Control	15	5	10	0	0	4	11	0
2019 Total	28	2	26	2	2	5	17	2
Treatment	13	0	13	2	0	3	8	2
Control	15	2	13	0	2	2	9	0
2020 Total*	16 / 13	7 / 5	9 / 8	4 / 2	2 / 1	4 / 6	6 / 4	0 / 0
Treatment*	8 / 6	1 / 1	7 / 5	3 / 1	0 / 0	3 / 4	2 / 1	0 / 0
Control*	8 / 7	6 / 4	2 / 3	1 / 1	2 / 1	1 / 2	4 / 3	0 / 0
Total*	75 / 72	19 / 17	56 / 55	6 / 4	4 / 3	18 / 24	45 / 43	2
Treatment*	37 / 35	6 / 6	31 / 29	5 / 3	0 / 0	11 / 12	19 / 18	2
Control*	38 / 37	13 / 11	25 / 26	1 / 1	4 / 3	7 /8	24 / 23	0

* Note: When two numbers are represented in a cell, the first represents the number of students analyzed for affective growth and the second represents the number of students analyzed for cognitive growth.

Table 5.3

Grade Levels of Students in Each Study

Group	*n*	7	8	9	10	11	12
2018 Total	31	0	0	10	7	11	3
2019 Total	28	1	1	3	12	4	7
2020 Total*	16 / 13	4 / 2	2 / 2	1 / 0	0 / 1	4 / 4	2 / 3
Total*	75 / 72	5 / 3	3 / 3	14 / 13	19 / 20	19 / 19	12 / 13

* Note: When two numbers are represented in a cell, the first represents the number of students analyzed for affective growth and the second represents the number of students analyzed for cognitive growth.

5.3.4. **Missing Data**

Across the three data sets, there were five values missing out of a total of 782. There were no values missing from the 279 total of the 2018 data set, and two values were missing from the 392 total of the 2019 data set. In the 2018 and 2019 studies, the authors gave their students surveys during class time. In the 2020 study, COVID-19 related issues led to the classes being shorter and required the surveys to be taken before the first day of class and after the last day of class. Three values were missing from the 178 total of the 2020 data set. There was no significant correlation between the values missing and the treatment or outcome variables, indicating that the values were missing at random. The five missing data points were imputed using simple linear regressions to predict their values based on the remaining variables in the construct (see Buck, 1960;

Jamshidian & Mata, 2007). This method should not have much impact on the outcome because the values were missing at random (Jamshidian & Mata, 2007).

5.3.5. **Effect Size**

We chose the bias corrected effect size measure Hedges' *g* to examine the difference in growth between students who used DIME maps and students who did not use DIME maps. Hedges' *g* with the bias correction factor is ideal in this situation with a low number of studies as it leads to results with a lower chance to overestimate a positive effect size than Cohen's *d* or Glass' Δ (Hedges, 1981). Because we had access to the raw scores, we were able to calculate the mean change-from-baseline as well as the standard deviation of that change. Conducting a meta-analysis on the change-from-baseline rather than post-intervention scores removes some amount of between-person variability from the analysis (Higgins et al., 2021). Therefore, the effect sizes reported represent the size of the effect associated with the treatment (using the DIME maps), the difference in change-from-baseline of the treatment group and change-from-baseline of the control group.

5.3.6. **Hartung-Knapp-Sidik-Jonkman Random Effects Model**

Meta-analyses with few studies are common but require special care. Over a review of 22,453 meta-analyses, Davey et al. (2011) found the median number of included studies to be three, with nearly 75% of the studies containing five or fewer studies. In some cases, researchers may have produced three studies on the same intervention, as in our own research, and sought to discuss overall findings. Traditional methods of random effects meta-analysis, when applied to a small number of studies with some heterogeneity, can be suboptimal and lead to high levels of error and poor generalizability (Günhan et al., 2020; Hartung & Makambi, 2003; IntHout et al., 2014). Alternative methods are needed to enable researchers to think and research meta-analytically in such situations (Günhan et al., 2020; Hartung, 1999). We explored these alternative methods and methodological options.

For this study, we chose to employ the Hartung-Knapp-Sidik-Jonkman (HKSJ) method. This method, often referred to as the Hartung-Knapp or equivalently the Sidik-Jonkman method, is designed to lead to lower false positive rates than traditional random effects (RE) methods under less than favorable conditions, such as in the case of very few available studies (Hartung, 1999; Hartung & Makambi, 2003; IntHout et al., 2014; Röver et al., 2015). The HKSJ method was a good way to reduce the risk of committing a Type I error.

The statistical package we used was Stata 16.1. This software allowed us to choose to calculate Hedges' *g* using the "exact computation for the bias-correction factor." It also enabled us to easily run a random-effects meta-analysis model using the HKSJ method, denoted the Sidik-Jonkman method in the options for Stata.

5.3.7. **Study Characteristics**

There were no published data sets that provided the data for this study. The 2018 and 2019 studies took place in a STEM summer camp held on a university campus. The

2019 study treatment group consisted of only male students. The 2020 study took place in an online STEM summer camp due to the COVID-19 pandemic.

5.4. Results

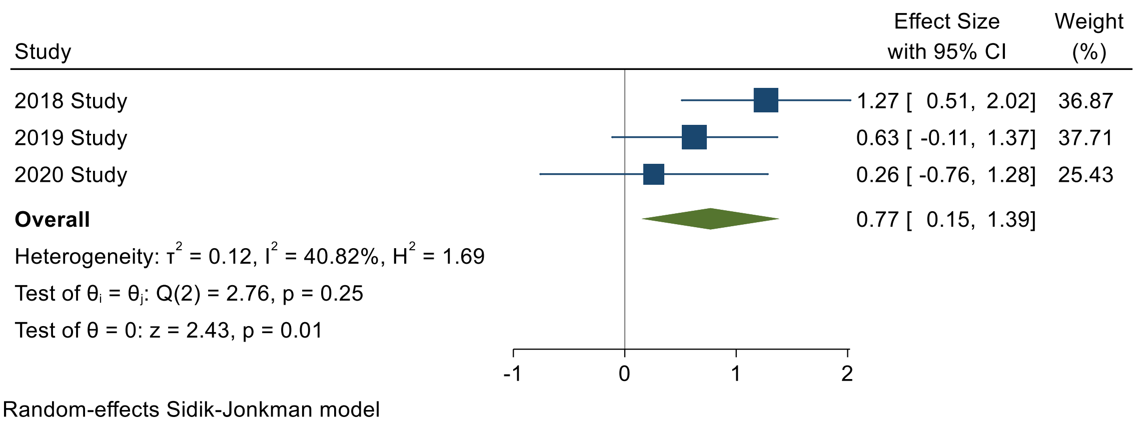
Two separate meta-analyses were run, one on the cognitive outcomes and another on the affective outcomes. Both outcomes are reported along with their accompanying forest plots. Conclusions and connections to prior literature are presented.

5.4.1. **Cognitive Outcomes**

The results showed that students using DIME maps gained significantly more on cognitive measures than students who did not use DIME maps (Hedges' $g = 0.77$, 95%CI = [0.15,1.39], $p < .05$). From this, we claim that use of DIME maps improved students' cognitive gains. See Figure 5.5 for a forest plot of the effect sizes from each study and the resulting overall estimate from the RE meta-analysis. In their meta-analysis of 24 studies involving interactive concept maps, Schroeder et al. (2018) found a similar overall effect size (Hedges' $g = 0.60$, 95%CI = [0.33,0.87]). This indicates that DIME maps performed similarly to interactive concept maps previously created. However, DIME maps have the advantage of being automatically generated by the DIME Map system, requiring less time and effort to create than a typical interactive concept map.

Figure 5.5

Forest Plot of the Cognitive Effect Sizes



5.4.2. **Affective Outcomes**

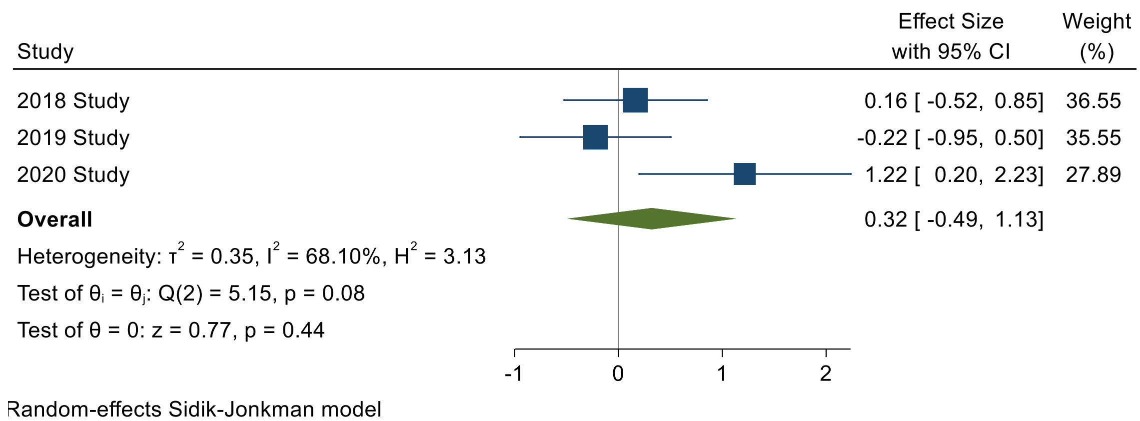
The results showed that students using DIME maps performed similarly on the affective measures as students who did not use DIME maps (Hedges' $g = 0.32$, 95%CI = [-0.49,1.13], $p > .05$; see Figure 5.6). When compared to the meta-analysis performed by Schroeder et al. (2018), this finding seems consistent, as the confidence intervals overlap. Although the overall effect size was small and positive, the results indicate that we cannot claim that students using DIME maps performed better than students who did not use the DIME maps on affective measures. These results are concerning but understandable, because concept maps have been shown to improve self-efficacy among experimental groups similarly to comparison groups that receive other effective treatment strategies (Chularut & DeBacker, 2004; Roshanger et al., 2020). We recommend that further studies investigate the affective effects of using DIME maps and with what conditions or populations using DIME maps might be most beneficial.

The lack of a significant effect on the affective measures could be explained through CATLM. Some students in each of the three studies expressed that they found the DIME maps initially complicated, representing too much complex and unfamiliar information at once. This finding aligns with the CATLM idea that such material can require an overwhelming amount of extraneous processing (Mayer, 2014; Moreno & Mayer, 2007). This educational theory concludes that in these instances, it is the goal of instructional design, and in this case the DIME maps, to assist in keeping essential processing at a manageable level. Further development of the levels of maps and what to initially present to a learner, possibly after testing their prior knowledge with a quick survey, could alleviate students' initial confusion.

Another reason that the self-efficacy gains were not greater might be because students encountered higher level physics concepts that they only could navigate with the DIME map; when asked about their ability to approach such concepts, they may have answered assuming they would not have access to the map. Unlike the self-efficacy questions in the 2018 and 2019 studies (Appendix A and Appendix D, respectively), the self-efficacy questions in the 2020 study asked students to imagine having "the right tools" when considering their self-efficacy in physics (see Appendix F). This change of wording and reflection may have led to the students feeling more enabled with DIME maps in terms of approaching learning complex physics concepts.

Figure 5.6

Forest Plot of the Affective Effect Sizes



5.5. Discussion

The outcomes experienced by our students using DIME maps aligned with prior research on CATLM and concept maps. Although the present study is consistent with the underlying theories and prior research, we do not attempt to pinpoint the exact mechanisms and features that led to those results. Rather, we examined DIME maps as an interactive educational technology designed to elicit meaningful learning through assimilation of new knowledge into prior knowledge structures. Further evidence is needed to examine the effects of altering individual design principles within DIME maps on learning outcomes. For example, changes to the way the system first presents DIME maps to users may prove to lessen the excess cognitive load and improve the attitude and engagement of confused students. Still, the findings are promising in that using DIME maps had a positive impact on students' cognitive outcomes, even when compared to other students engaged in project-based and collaborative learning. This potentially demonstrates the added benefit that DIME maps can have, such as the fact that teachers can use the online system to automatically produce DIME maps for any PDF textbook chapter. Additionally, students may find benefits using DIME maps to help understand the interrelationships between concepts. Through ongoing upgrades to the system, we are investigating ways to present different maps to different students based on their prior knowledge. Automatically generated, interactive, and soon to provide differentiated learning for individual students, DIME maps represent an evolution of concept maps.

There were several limitations to this study, including the impact of COVID-19, small sample sizes, a small number of included studies, and potential conflict of interest. COVID-19 had a disruptive effect on the data collection for the 2020 summer camp (which was held through Zoom), as the amount of time students spent in class was reduced. To compensate and allow for full instruction and engagement time, we sent the pretest before the first day and the posttest after the last day of class. The response rate for the 2020 study suffered greatly—approximately 45% compared to the previous response rates of 100% for both the 2018 and 2019 studies. Another limitation is that because of the small overall sample size ($n = 75$ responses for affective outcomes, $n = 72$ responses for cognitive outcomes) and the small number of included studies ($n = 3$), we chose to use the HKSJ method in our RE meta-analysis, which helped to avoid overestimating the effect. Finally, it is nearly impossible to minimize bias in this study because we are the sole developers and testers of DIME maps. To address this, we attempted to make this work transparent and replicable with all methodological decisions made a priori or before the analysis of data. It is also important to note that due to the small and relatively homogeneous overall sample, it was impossible to conduct any moderator analyses or examine the effects of using DIME maps under various conditions or with specific populations. We recommend that the next step is to explore improvements and variations on the DIME Map system according to feedback received over the past three years and to design studies to investigate whether the same effects hold for varied populations and implementations.

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6. CONCLUSIONS

6.1. Intellectual Merit

Because dynamic and interactive mathematical expressions (DIME) maps are essentially interactive and automatically generated concept maps, we hypothesized that DIME maps would have similar effects on students' learning outcomes. Students used DIME maps to navigate their portable document format (PDF) textbooks and engage in self-guided research; this was especially true for the research phase, the ideate phase, the analyze ideas phase, and the communicate and reflect phase of the engineering design process (Chapter 2; see also Morgan et al., 2013). Students expressed that DIME maps enabled them to see how all the concepts that they were learning were interconnected. This finding was consistent with research on concept maps, in which understanding the interconnections between concepts has been found to be essential for meaningful learning (Cliburn, 1990; Novak, 1998; Novak & Musonda, 1991). Concept mapping and even the use of interactive concept maps have been shown to improve students' cognitive outcomes (Schroeder et al., 2018). We have provided evidence that using DIME maps has led to positive effects on students' cognitive outcomes (Chapters 3 and 5). However, while an initial potential relationship was explored between using DIME maps and self-efficacy, we were unable to establish a generalizable statistically significant effect (Chapters 3, 4, and 5). We suggest that this may be due to the initial visual complexity of DIME maps, as commented by several students (Chapters 3 and 4).

Still, we established that students who interacted more with DIME maps gained more in self-efficacy (Chapter 4). It is important that future works explore the potential situations and populations for which using DIME maps might have the greatest effect for self-efficacy.

After exploring an initial example and discussion about using DIME maps in science, technology, engineering, and mathematics (STEM) project-based learning (PBL; see Chapter 2), we rigorously explored the relationship between using DIME maps and two particular learning outcomes (Chapter 3). Through a randomized experimental study and MANOVA, we found a multivariate relationship existed that implied that DIME maps had a positive effect on a students' self-efficacy in physics and understanding of connections between content knowledge. All of these outcomes aligned with prior literature; DIME maps are similar to concept maps, and concept maps have been shown to have a positive impact on both cognitive and affective outcomes (Schroeder et al., 2018). On examining the effect size on the individual learning measures, we concluded that using DIME maps was associated with a positive effect on cognitive outcomes, using DIME maps had no statistically significant effect on affective outcomes, and that there was no statistically significant interaction between gender and use of DIME maps for the outcomes of interest. Qualitative findings indicated students valued DIME maps as a tool to improve meaningful learning through interactive elements and visual representations of the relationships between concepts. Some students claimed that DIME maps were initially complex.

We sought to determine whether students persisted through initial complexity and whether overall user interactions with DIME maps was positively correlated with self-efficacy gains (Chapter 4). We found that user interactions were significantly correlated with several of the questions on the survey. We presented our findings as a first step in an analysis of user interactions as called for with dynamic and interactive learning tools (Jenkinson, 2009). Analysis of user interactions has been shown to be a valuable indicator of participation and engagement with interactive textbooks (Liberatore et al., 2020). Because of the correlation between user interactions and gains, we also recommended requiring or at least monitoring students' user interactions with new educational technologies.

In the fifth chapter of this dissertation, we meta-analytically compared the data from all three years of the implementation of DIME maps and preliminarily concluded that students who used DIME maps gained significantly more on cognitive measures than students who did not. This finding further confirms what was found in Chapter 3 and in meta-analyses of concept mapping studies, where using similar tools was associated with similar cognitive gains compared to traditional teaching and learning methods (Schroeder et al., 2018). Students who used DIME maps experienced gains in self-efficacy in physics similar to the gains experienced by the comparison groups who were all taught with PBL. Previous studies have found significantly greater gains in self-efficacy for students using concept than students using traditional strategies such as lectures or textbook reading (Adiyiah et al., 2020; Schroeder et al., 2018), however no difference has been detected between using concept maps and receiving other effective educational teaching strategies (Chularut & DeBacker, 2004; Roshanger et al., 2020). In our studies, the students in the control groups were still learning via PBL. This could explain why students in the control groups had similar gains in self efficacy, because PBL has been shown to have a positive influence on self-efficacy (Shin, 2018). Still the large confidence interval and generally positive results indicate room for further investigation into the effect of DIME maps on self-efficacy.

The positive impact of DIME maps on cognitive outcomes has important implications for the underlying theories of the cognitive-affective theory of learning with media (CATLM) and assimilation theory. In this dissertation, we have confirmed and provided additional insight into the underlying theories of learning. While we observed students occasionally encountering confusion and high extraneous cognitive load upon first viewing DIME maps, this was not unexpected. Researchers have found similar results for concept maps and have warned to be wary of map structure (Amadieu et al., 2010) and of the scale and complexity of the map (Blankenship & Dansereau, 2000). The coherence and redundancy principle of CATLM builds on the assumption that students have limited visual working memory with which to process and store new learning (Moreno & Mayer, 2007). Therefore, it is important for future implementations of DIME maps to be preceded by training or to gently transition students from simple maps to more complex maps.

6.2. Broader Impacts

There is value in this work to society and for specific populations of students and teachers. In this dissertation, I have shown a clear link between DIME maps and concept maps in their visual representation and theoretical underpinnings. The DIME Map system can democratize learning for students who could benefit from learning accommodations. Use of concept maps has been tied to increased benefits for English as a second language (ESL) students when compared to students whose native language is English (Chularut & DeBacker, 2004). One explanation for this could be that acquiring academic vocabulary poses additional barriers for ESL students. Concept maps help ESL students focus on major concepts and the relationships between those concepts instead of the extraneous difficulty of navigating the English language while learning new concepts. I have previously explored how STEM language can be considered another language requiring careful consideration by teachers and students (Kwok et al., 2020; Rugh et al., 2018; Rugh, Chang, et al., 2021). By presenting the mathematical formulas and STEM language vocabulary, DIME maps are similar to bilingual knowledge maps, but with STEM language and the language of mathematical formulas, and using bilingual knowledge maps has been shown to improve vocabulary acquisition for second language learners (Bahr & Dansereau, 2001). Because of the visual representation of concepts and relationships, students can use DIME maps to approach learning content knowledge that was previously inaccessible because of language barriers. Students expressed how DIME maps made the connections between concepts clear and understandable (Chapter 3). Students also appreciated how they could maneuver the DIME maps to create a representation of knowledge that fit their individual understanding and abilities. Personalizable and dynamic, DIME maps can potentially be an automated and individualized educational technology for differentiated learning. It is my hope that we will soon be able to have DIME maps evaluate and build student-specific maps based on a brief prior knowledge survey.

In Chapter 3, we found some evidence that using DIME maps could have a gap-closing effect on learning outcomes for female students. In the control group, female students were outperformed by male students in terms of gains in both cognitive and affective learning outcomes. The opposite occurred in the experimental group—female students who used the DIME maps outperformed male students who used the DIME maps in terms of gains in both cognitive and affective learning outcomes. However, the 2019 and 2020 studies did not have a sufficient number of female students to investigate this further. Therefore, further research is warranted to investigate whether using DIME maps would have a greater impact on students who are not well-served by traditional instruction and textbook learning.

Teachers can use the DIME Map system to turn many textbooks (that are in PDF format and contain concepts associated with mathematical variables, expressions, and formulas) quickly and effectively into interactive textbooks. This feature makes DIME maps especially important for under-resourced schools, where teacher burnout and fatigue are especially prevalent (Bottiani et al., 2019). New DIME maps can be automatically generated by teachers and students uploading a PDF textbook chapter into the DIME Map system. After several minutes, a new DIME map is permanently created and can be accessed by multiple students with the click of a button. Each student interacts with their own iteration of the DIME map, making their DIME map personalizable and dynamic based on their interactions. Future developments in the system will explore the automatic generation of concept maps from non-mathematical texts.

In this dissertation, I presented four articles in which my research group and I proposed, developed, and evaluated early versions and implementations of DIME maps. I hope this work can serve as a foundation for future explorations into artificial-intelligence-generated dynamic and interactive concept maps.

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APPENDIX A

2018 AFFECTIVE SURVEY

Please circle one number for each statement that corresponds with how you feel about that statement.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
1. I feel that complex physics concepts are approachable.	1	2	3	4	5
2. I am comfortable exploring new topics in physics.	1	2	3	4	5
3. I understand ways in which physics concepts are related to each other.	1	2	3	4	5
4. I am able to learn difficult physics concepts.	1	2	3	4	5

APPENDIX B

2018 COGNITIVE SURVEY

1) Moment of inertia is used to calculate:
    a. Angular velocity
    b. Angular momentum
    c. Rotational kinematic energy
    d. Angular displacement
2) Energy in a fixed axis rotation system relies on:
    a. Moment of inertia
    b. Angular velocity
    c. Angular displacement
    d. Time
3) A 10kg point mass travels around a circle of radius 5m at an angular velocity of 3 radians per second. What is its angular momentum?
4) Increasing radius and keeping mass constant causes the moment of inertia to:
    a. Decrease
    b. Remain the same
    c. Increase
5) If an object's angular velocity stays constant, then its rotational kinetic energy remains constant. True / False

APPENDIX C

2018 INTERVIEW PROTOCOL

1. What was your first impression of this map?
2. Did the map help you to approach things differently? To learn differently?
3. Was there any one feature that you found more helpful?
4. Did you see the system improving your understanding of math or science material?
5. Did you use the system throughout the week to browse the material?
6. How useful was this system compared to traditional textbooks and reading?
7. Did you notice the colors on the map? Did they mean anything?
8. What kind of additional controls would you add to the graph to help understand the text better?
9. Would you use the tool to create your own graph and share it with other students?
10. If the graph could learn from the changes, how you use the system, would you like it to build a profile for you, that way the next time you open it the default graph is more meaningful just for you?
11. Would you consider competing with other students to see who could make the best graph?
12. Would you want to use this tool to learn mathematics or science in your next school year?

APPENDIX D

2019 AFFECTIVE SURVEY

Think about your current activities as a student. Read each of the following statements **carefully**, then circle the number that best represents your response, where:

0 indicates: I am **definitely not able** to do this. 10 indicates: I **can definitely** do this *Circle the appropriate number:*

1	I am able to visualize ways in which physics concepts are related to each other	0 1 2 3 4 5 6 7 8 9 10
2	I am able to learn difficult physics concepts	0 1 2 3 4 5 6 7 8 9 10
3	Soon after science class is over, I am able to remember *most* of the key concepts	0 1 2 3 4 5 6 7 8 9 10
4	Soon after science class is over, I am able to remember *all* of the key concepts	0 1 2 3 4 5 6 7 8 9 10
5	I can understand *most* of the key concepts covered in my science classes	0 1 2 3 4 5 6 7 8 9 10
6	I can understand *all* of the key concept covered in my science classes	0 1 2 3 4 5 6 7 8 9 10

* Note that questions 3 and 5 were not included in the meta-analysis but intended to improve the discriminative power of questions 4 and 6 respectively.

APPENDIX E

2019 COGNITIVE SURVEY

Here is a randomized list of the concepts that we will cover in this class. Please write a brief description of what you think these concepts are. Also write down symbols, units, or formulas that you believe may be related to these concepts:

Centrifugal Force –

Angular Displacement –

Angular Momentum –

Angular Velocity –

Rotational Inertia –

Angular Acceleration –

Degrees –

Centripetal Force –

Radians –

Rotational Kinetic Energy –

APPENDIX F

2020 AFFECTIVE SURVEY

There are no right or wrong answers. Please answer each question as naturally and honestly as you can. Answer the following statements by placing the marker wherever on the line between the two end points (strongly disagree and strongly agree) that matches your feelings about the item.

Leave the slider at -1 (all the way left) to indicate that you are unwilling to answer or are unable due to unfamiliarity with physics as a subject. Rate from 0 (Strongly Disagree) to 100 (Strongly Agree)

1) With the right tools, I can handle advanced content in physics
2) With the right tools, I am good at projects involving physics
3) Even with the right tools, physics is difficult for me

APPENDIX G

2020 COGNITIVE SURVEY

Skip any concepts that you are unfamiliar with.

Write a brief description of what you think these concepts are.

Centrifugal Force	
Angular Momentum	
Moment of Inertia	
Radius	
Rotational Kinetic Energy	
$I = \sum mr^2$	
$\omega = \frac{\Delta\theta}{\Delta t}$	
$\frac{\Delta L}{\Delta t} = 0$	