Improving Self-Efficacy With Automatically Generated Interactive Concept Maps: DIME Maps

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Abstract: The Dynamic and Interactive Mathematical Expressions (DIME) Map system automatically generates DIME maps, which are personalizable and manipulable concept maps that allow students to interact with the mathematical concepts contained in any portable document format (PDF) textbook or document. A teacher can automatically upload a PDF textbook chapter and retrieve a DIME map of the contained mathematically based concepts. The DIME map is interactive and manipulable and can be used to interactively navigate the PDF textbook chapter. Our goal was to investigate the relationship between use of DIME maps and student learning outcomes, including self-efficacy and ability to understand and recall connections between physics concepts. We implemented a pretest/posttest to determine if student self-efficacy and connections in knowledge increased after participation in a summer camp physics class. We additionally conducted student interviews to better understand how changes in these two factors may have occurred. We then used multivariate analysis of variance and thematic analysis, finding and investigating positive effects of students using DIME maps, namely growth in self-efficacy and connections in knowledge. Based on our findings, we conclude that DIME maps can be valuable learning tools for students that have positive effects on both cognitive and affective learning outcomes.

Keywords: Technology integration, Concept mapping, Mixed methods, Physics, STEM

1. Introduction

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 (Horton, Lovitt and Bergerud, 1990; Guo, et al., 2020). In education settings, graphic displays of information can be provided as advance organizers prior to students' learning to present a road map for potentially challenging material (Ausubel, 1968; Githua and Nyabwa, 2008; Chuang and Liu, 2014). Doing so potentially has positive learning outcomes, as there is evidence that when introduced to the material beforehand students learn more from lectures covering difficult concepts (Schwartz and Bransford, 1998; Stelzer, et al., 2009). Concept maps have also been shown to reduce cognitive load by providing students an alternative visual representation of the connections between ideas or concepts (Novak, 1998; Hill, 2005; Stull and Mayer, 2007; Özmen, DemİrcİoĞlu and Coll, 2009). 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.

2. 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 and 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; Mayer, 1979; Dexter, Park and Hughes, 2011). 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.

Reference this paper: Rugh, M.S., Capraro, M.M. and Capraro, R.M., 2023 Improving Self-Efficacy With Automatically Generated Interactive Concept Maps: DIME Maps, *The Electronic Journal of e-Learning, 21(3)*, pp 141-157, available online at www.ejel.org

2.1 Theoretical Framework

This study was built on the theoretical foundation of assimilation theory, which states that meaningful learning occurs when students assimilate, or anchor, new concepts into their existing prior knowledge structure (Ausubel, 1968; Ausubel and Robinson, 1969; Ausubel, Novak and Hanesian, 1978; Gardee and 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. With this theoretical framework in mind, we propose that the intervention used in this study supports making connections between prior knowledge and new concepts, thus leading to more meaningful learning and improved self-efficacy.

2.2 Technology and Concept Maps

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 and Abu-Alhija, 2018). Several researchers have shown that concept mapping has been connected with improved academic self-efficacy (Chularut and DeBacker, 2004; Adiyiah, Mutangana and Ameyaw, 2020; Roshanger, et al., 2020). On this foundation, we sought to see how technology could be harnessed to maximize the potential for concept mapping.

Designers of electronic concept maps have benefited greatly from recent technological developments. For instance, Cañas, et al. (2004) created CmapTools to aid in the construction, publishing, and sharing of electronic concept maps. To further aid in sharing concept maps, Cañas, Carff and Lott (2018) later created eCmap, which is a concept map editor that can be embedded easily into HTML for use on websites. In addition to showing connections between abstract text-based knowledge, technology-enhanced concept maps have the capability to display multimedia information (Kornilakis, et al., 2004; Tergan, Keller and Burkhard, 2006; Hsieh, Chu and Yang, 2018). Developments in technology have allowed concept maps to become interactive, further increasing the potential for student engagement in learning (Dowell, 2016; Wang, 2016), and both traditional concept maps and interactive concept maps have been associated with positive gains in cognitive and affective measures (Schroeder, et al., 2018).

There are several types of interactivity in multimodal learning environments that can improve learning (Moreno and Mayer, 2007). Some interactive concept maps display additional information when users click on individual nodes (McClellan, et al., 2004; Dowell, 2016; Wang, 2016), and others allow users to easily add nodes and links with a few clicks (McClellan, et al., 2004; Wang, 2016). Another type of interactivity used by some interactive concept maps is allowing users to mark, note, or highlight individual concepts (McClellan, et al., 2004; Dowell, 2016). In each of these examples, interactive elements were added to electronic concept maps to improve creation and consumption of concept maps.

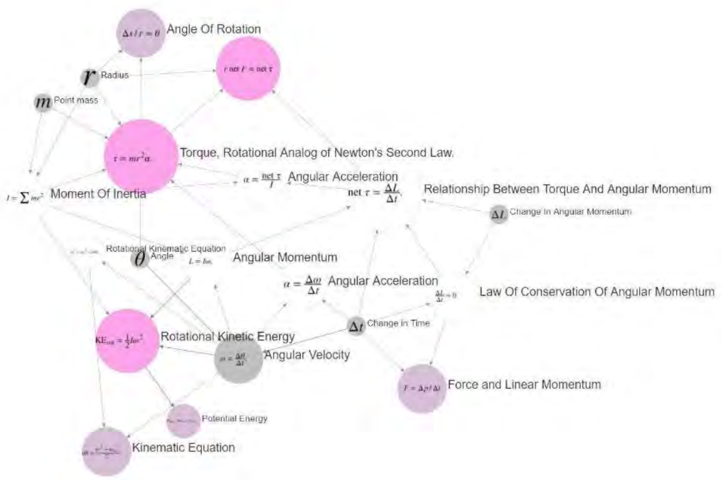
Although interactive concept maps have much to offer, they are still tedious to create, posing a significant obstacle to regular use in classroom settings by heavily burdened teachers. McClellan, et al. (2004, p. 2) suggested, "It would be extremely difficult and tedious to process the whole book (by hand) to add relevant resources to each and every concept; and the resulting linkage of resources to concepts would be static". Their solution at the time was to create a concept map software, CNT, that allows a person to define a list of concepts. The system would then search a textbook for occurrences of those concepts and link them to a student-generated concept map so that users could quickly navigate relevant content in their course materials. The strength of this concept map software is that it significantly reduced the load of both teachers and students in creating an interactive concept map, but users still needed to develop an initial concept map for the software to connect content to. In more recent years, various researchers have examined the efficacy of using algorithms to generate concept maps, thereby removing the need for an expert to create a concept map (see Atapattu, Falkner and Falkner, 2017; Shao, et al., 2020). The algorithm developed by Atapattu, Falkner and Falkner (2017) required the use of pre-existing lecture slides, however, which still require an expert to create, and that of Shao, et al. (2020) utilized only natural language processing that requires the setting of parameters before implementing text analysis. The concept maps produced by both of these systems are effective for improving student learning, but their implementation is still limited by the necessary intervention of an expert in setting the boundaries of their creation.

Clearly, previous interactive concept maps and concept map-developing algorithms have provided many tools for both concept map creators and consumers. However, to our knowledge, no existing concept mapping system provides the means for the truly automatic generation of concept maps, producing concept maps without the need for experts or instructors to set parameters or even input data. The DIME Map system we developed provides a significant reduction in effort and time required to create concept maps because an uploaded portable document format (PDF) text is automatically parsed by the DIME Map system to create a meaningful interactive concept map. Importantly, this can be done by any individual with access to a PDF text file, including students. We propose that DIME maps provide many of the same benefits of previous interactive and technology-enhanced concept mapping systems with the added benefit of automatically generating concept maps using an artificial intelligence (AI) system.

2.3 DIME Maps

With the intent to help students learn mathematical ideas, a team of computer science engineering researchers developed the DIME Map system (Wang, et al., 2018; Beyette, et al., 2019; Rugh, et al., 2019; Rugh, et al., 2021;). The DIME Map system automatically provides a concept map of interconnected topics and equations. This outcome is achieved by the AI system which algorithmically carries out three major steps: 1) identifying mathematical objects, including variables (e.g., *x*), expressions (e.g., mc^2), and equations (e.g., F = ma); 2) identifying the names or definitions of those mathematical objects using natural language processing; and 3) finally representing those mathematical objects as an interactive concept map with meaningful links. The links, or arrows, between concepts all have the same meaning and indicate how certain concepts "build into" others; for example, an arrow from *mass* to *force* indicates that mass "build(s) into" force. 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.

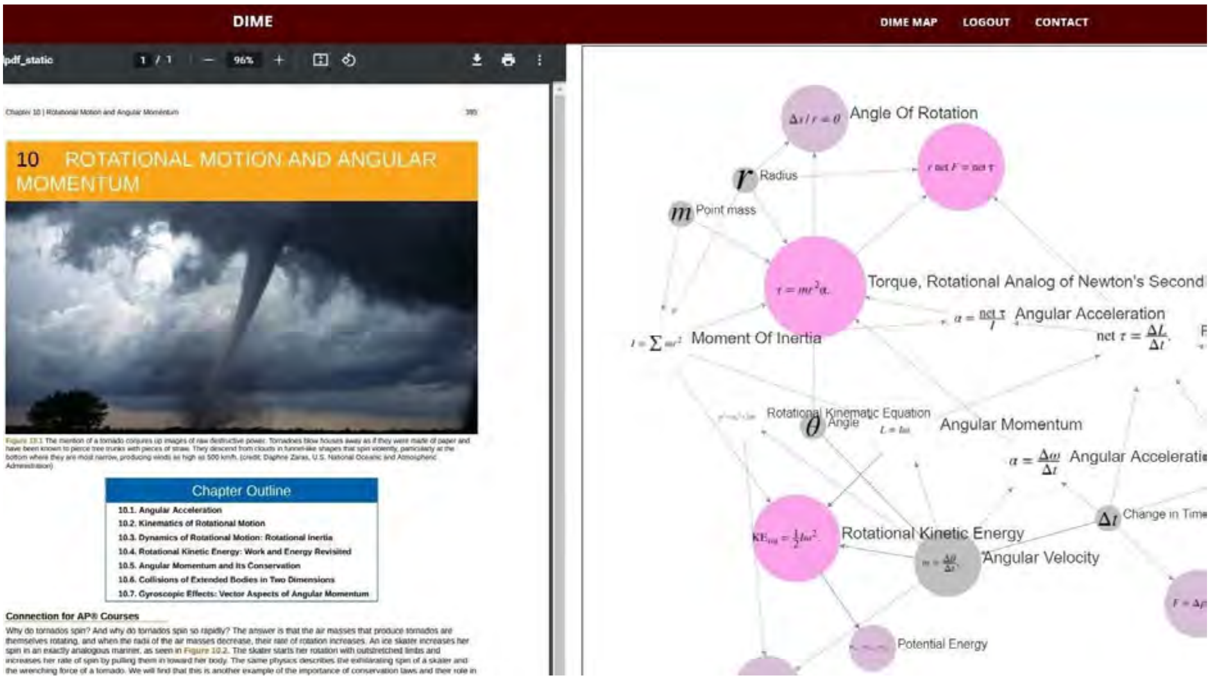
This "road map" of interconnected topics manifests itself through the DIME map, which uses links, arrows, and spatial arrangement to highlight both key concepts and structural relationships (see Figure 1). The DIME Map system removes redundant elaborations found in texts and covers only the key fundamental 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, Falkner and Falkner, 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.



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

Figure 1: An Example DIME Map

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 PDF text document (see Figure 2). This format for displaying the textbook on the left and the concept map on the right is similar to previous interactive concept maps designed by Wang (2016). 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. 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.

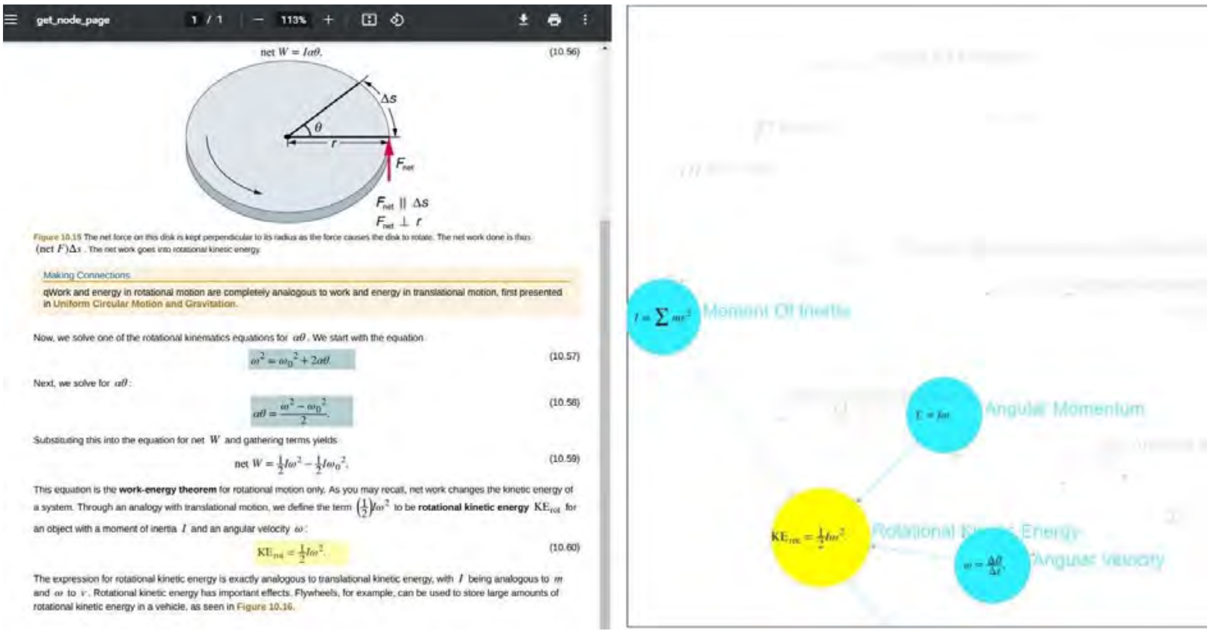


Note. This figure provides a visual example of how a DIME map is displayed next to original text. Not intended to be readable.

Figure 2: A DIME Map (Right) and PDF Textbook (Left)

Those using the DIME Map system can interact with their maps through multiple additional 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). 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. Other concept mapping systems that utilize interactive elements have proven effective at improving the cognitive (content knowledge) and affective (emotion towards content) outcomes for learners (Schroeder, et al., 2018). There has yet to be a study examining whether a fully AI-generated interactive concept map yields similar learning outcomes. The purpose of this small-scale pilot study was to test whether DIME maps are indeed an appropriate alternative to traditional instruction.



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.

Figure 3: A DIME Map and PDF Textbook Focused on One Concept

2.4 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:

- Is there a multivariate relationship or pattern between using DIME maps and two learning outcomes for students:
  - o *self-efficacy towards learning physics,*
  - o *and understanding connections between content knowledge?*
- How do students feel about using DIME maps—what aspects of DIME maps do students consider helpful or harmful to their learning process?

3. 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 (Morse, 1991; Leech and Onwuegbuzie, 2009). This study design was deemed appropriate for the current study because although measuring learning outcomes provides data on the success of DIME maps as a learning tool, data on student user experience is necessary to understand if DIME maps help students connect new information to previous knowledge in similar ways to other concept maps and where they may potentially fall short. In the current study, we collected pretest and posttest scores of students' cognitive and affective learning in a physics class and then conducted interviews to understand how and why these scores may have changed. The resulting data allowed us to determine if computer-generated concept maps have the same efficacy as other interactive digital concept maps in improving student learning outcomes.

3.1 Participants and Setting

Participants included 31 high school students who attended a science, technology, engineering, and mathematics (STEM)-oriented summer camp in 2018. Summer camp attendees selected four of eight possible classes to enroll in while attending the camp, which included physics, robotics, coding, and other topics. Students were then immersed in 1.5-hour daily sessions for each selected class for four to five days total. The participants in the current study (*N* = 31) included those students who enrolled in the physics class, which engaged students in project-based learning (PBL) while exploring mathematical and physics concepts. These students were randomly assigned to one of two groups before the first day of camp: 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). 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 and Yang, 2019). 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. Importantly, none of the students had taken a physics class in school, so the participants all began the study with similar levels of formal physics instruction and knowledge. 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.

For the purposes of this study, an overall sample size of 31 was sufficient, as analysis was to be done using a simple multivariate analysis of variance (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. As such, the sample size was more than adequate for the current study.

The physics behind fixed-axis rotation comprised the content covered in the class. Both sections of the physics class were 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 only deviation that occurred was that the treatment group was also instructed on how to use the DIME Map system. 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 of course curriculum. 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 Data Sources

One pre/posttest for both *Self-efficacy* and Connections in Knowledge (*Connections*) was administered to determine the effects of student participation in the physics class on these affective measures. The instrument was written by the physics teacher for the STEM summer camp and first vetted by research faculty in the Colleges of Science and Education at an R1 University, 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). To test for internal consistency, we calculated that the Cronbach's alpha was sufficient across Self-efficacy ($\alpha = .8348$) and across Connections ($\alpha = .4286$), indicating that the questions intending to measure self-efficacy were closely related to each other, and the questions intending to measure connections in knowledge were also closely related to each other (although less so). Self-efficacy specifically 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 and 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, as we determined that students with greater familiarity with the DIME maps would provide richer data and insights than students who utilized the DIME maps less. After conducting interviews with the three selected students, our data reached saturation and we stopped hearing new ideas or themes in the students' responses, so further interviews were determined to be unnecessary. For the purpose of confidentiality, the three students interviewed will be referred to under the pseudonyms Alice, Bailey, and Chris. We recorded audio from the interviews to later transcribe and analyze.

3.3 Data Analysis

The quantitative data were analyzed using MANOVA in SPSS 24, 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 is 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, Morris and Richler, 2012). To account for the 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 and 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 and 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.

4. 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.

4.1 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 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, a MANOVA was a suitable choice for the analysis of these two new data groups. The adjusted R^2 effect sizes were small and relatively unimportant. Therefore, the random assignment of the participants and the pretest results allowed us to conclude with reasonable certainty that any obtained effects were due to the intervention and use of the DIME Map system.

Table 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	-0.200	2.049	5	2.800	1.789	0.200	.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 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 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). 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 although 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: 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.

4.2 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.

4.2.1 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. In this way, the interviewed students made clear how DIME maps improved their Connections in Knowledge growth.

4.2.2 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 opportunities and propensities. It is here that we see the DIME map making a larger difference. When asked whether DIME maps helped her to learn differently, this was Alice's response:

> *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 (Horton, Lovitt and Bergerud, 1990; Dexter, Park and Hughes, 2011). 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". Although 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 and 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, making them feel that they could learn faster and more easily, important aspects of self-efficacy in learning physics..

4.2.3 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 that students enjoyed is in its search feature, which finds instances of term occurrences in both the textbook and the map. "I thought it was really good for finding one section", Bailey commented. Through these observations, we determined that by reducing cognitive load in the learning process, DIME maps improved students' Connections growth.

4.2.4 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, Williams and McKenna, 2018) and deeper learning of concepts (Evans and Cuffe, 2009; Irvine, Williams and McKenna, 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. In summary, students who used DIME maps became more empowered learners and developed self-efficacy through concept mastery and peer teaching experiences.

4.2.5 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 selected physics textbook chapter (see Figure 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 at once 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 and 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 AI.

5. Discussion

Through this study we extend the research on concept mapping by determining that automatically generated concept maps using an AI system are an effective alternative to traditional instruction. Previous algorithms designed to help construct concept maps have proven effective at improving student content knowledge but required teacher or expert input in order to create a concept map (see McClellan, et al., 2004; Atapattu, Falkner and Falkner, 2017; Shao, et al., 2020). The current study brings the field forward by examining the effects that a fully automatic concept mapping system, the DIME Map system, has on student cognitive and affective learning outcomes. Our findings suggest that DIME maps have similar positive effects on student learning as previous concept mapping systems but with the added benefit of relieving teachers of the burden of concept map creation. The success of DIME maps derives from several factors.

Like concept maps before them, DIME maps can provide a means to reduce cognitive load, and this characteristic comes from the way the system approaches mathematical or symbolic language (see Hiebert, 1988; Goldin and Kaput, 1996; Esteve, 2008; 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 doing so, 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). In this way, DIME maps address the reality of the disciplinary language as a potential gatekeeper to student mathematical success.

Cognitive load on students is additionally reduced by the ability of DIME maps to visually represent the complexity of mathematics. For many students, the syntax and semantics of algebra, which often integrate aspects of other formulas (Capraro, et al., 2010; Rupley, et al., 2011), is a complex web that is difficult to understand. To approach such complexities, students using DIME maps can easily track a complex formula back through its development using a wide variety of interactive features and meet immediate personal learning needs. 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 and Mayer, 2007). Although we have seen that DIME maps offer high levels of interactivity and ease cognitive load, future research is needed to investigate what multimodal design principles are present in DIME maps and support deep cognitive processing.

An additional benefit that DIME maps have over traditional instruction concerns 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.

The DIME map system has further implications for future research, specifically on how connections between the text intended to teach mathematics and symbolic representations emerge for students (see Hiebert, 1988; Godino, Batanero and Font, 2007). Because 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 between each node displayed across chapters as well as see how those concepts develop and build upon each other. 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. Future research may examine how students navigate the web of connections the DIME Map system develops from a textbook chapter and if their structure of understanding follows the pathways set forth in the textbook.

The limitations of the current study necessitate further research on student cognitive and affective benefits from DIME maps as well. The setting of a STEM summer camp physics class the students self-selected into provided participants who were already motivated and interested in learning the topic. Future studies should seek to implement the DIME Map system in formal learning settings to more deeply examine potential benefits that DIME maps may have over traditional instruction. Furthermore, the small sample size of three student interviews, while appropriate for the current study, does limit our understanding of the mechanisms that enable DIME maps to improve student connections in knowledge and self-efficacy in physics. Future research should thus analyze the effects of DIME maps on larger groups and across more variables, and this will enable education researchers and instructors to better understand how DIME maps may prove to effectively improve understanding, retention of knowledge, and self-efficacy for high school students in mathematics.

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Appendix A

		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

Please write your answers in the blanks provided. Each question **may have more than one answer**.

EXAMPLE: If A and B are correct, please write both answers.

1. Moment of inertia is used to calculate:
   a. Angular velocity
   b. Angular momentum
   c. Rotational kinetic 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 10 kg point mass travels around a circle of radius 5 m 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.
   a. True
   b. False

Appendix C

- What was your first impression of this map?
- Did the map help you to approach things differently? To learn differently?
- What is one feature of the tool that you found helpful?
- Did you see the system improving your understanding of math or science material?
- Did you use the system throughout the week to browse the material?
- How useful was this system compared to traditional reading?
- Did you notice the colors on the map? Did they mean anything?
- What kind of additional controls would you add to the graph to help understand the text better?

- If it was possible for you to create your own graph, would you do that and share it with other students?
- Would you consider competing with other students to see who could make the best graph?
- Would you want to use this tool to learn mathematics or science for school next year?