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A physics instructor's enactment of three-dimensional learning: Action research

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Abstract

This action research study was conducted in a physics education class focusing on electricity and magnetism. The instructor aimed to integrate three-dimensional learning into curriculum, lesson planning, and instruction to understand successes and challenges of teaching through a new approach and students' perceptions of their learning process. The data collection included instructor's lesson planning, pre- and post-lesson reflections, student artifacts, and students' reflections. The qualitative data were analyzed through constant comparative method to identify theory-driven and data-driven codes, determine their frequency to categorize and construct themes. The results were provided with three themes: (1) the instructor's integration of three-dimensional learning, (2) the strengths and challenges of the implementation, and (3) students' experiences. These findings suggested the need for focusing on developing teachers' knowledge in different domains connected to each other such as scientific practices, crosscutting concepts, subject matter knowledge, and nature of science for student conceptions and instructional strategies.

Keywords: three-dimensional learning, action research, physics education

INTRODUCTION

Recent reforms in science education calls for a change in science teaching and learning practices to focus on constructivist pedagogies and enhance students' active involvement through exploring, data collection and analysis, and making explanations rather than traditional teacher-centered strategies (Felder & Brent, 1996; Huff, 2016; Krajcik & Merritt, 2012; National Research Council [NRC], 2015). However, there is teacher resistance to shifting or moving science learning away from knowledge transfer towards student-centered instruction. Science teachers need professional development and experience around constructivist pedagogies to focus on meaning-making of an individual through actively engaging in the experiences and understanding from the new experience in a different way (Haag & Megowan, 2015). This also emphasized the need for innovative curriculum, alternative learning environments, and classroom technologies (Beichner et al., 2007; Mazur, 1997; McDermott, 1996). These resources aimed to improve students' learning experiences through working actively, collaborating with others, and scaffolding while engaging in design of experiments, collection and analysis of data, and communicating scientific knowledge (Rutberg et al., 2023). A study by Etkina (2015) argued that teachers' and learners' engagement in scientific practices, which defined the activities scientists engage in when constructing and applying knowledge has been crucial component of teaching and learning science.

Research on pre-service and in-service science teachers' conceptions, knowledge, and beliefs has a great importance in science education to study their knowledge of content, pedagogy, and curriculum on a particular field such as physics, chemistry, and biology. Duit (2014) emphasized that physics teachers need to develop knowledge of physics concepts in different topics such as mechanics and electricity and magnetism in order to design lesson plans and enact them according to students' needs. Etkina (2010) discussed the course design process to develop physics teachers' pedagogical content knowledge (PCK) on different topics focusing on

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Contribution to the literature

- The article contributes to the current literature through highlighting the experiences of a physics instructor integrating three-dimensional learning into an elective teacher education course.
- This work can guide other science instructors to understand the problems in their teaching and act towards a resolution.
- Reform suggestions can be addressed through future action research studies.

instructional strategies, curriculum, and student conceptions. According to Krakehl et al. (2020), physics teachers might have lack of teaching experience and subject matter knowledge, occupational stress, inadequate support from other teachers and administrators that might also influence students' learning in science. Kelly (2013) indicated that teachers had challenges with standardized testing and lack of curricular autonomy to promote physics learning through differentiated activities. Milner-Bolotin et al. (2016) examined physics teacher candidates' development of PCK using interactive engagement pedagogies including peer instruction and PeerWise online platform in physics methods courses. The results showed the benefits of using conceptual multiple-choice questions to enhance teacher candidates' active learning through collaboration.

This reflective inquiry addresses action research methodology to understand the experiences of a college physics instructor as a teacher-researcher, who teaches a course on electricity and magnetism to develop pre-service science teachers' conceptual knowledge while implementing three-dimensional learning to address the reform suggestions and develop knowledge of three-dimensional instruction. The purpose of this study is to examine how a college physics instructor incorporates three-dimensional learning into a physics education course on electricity and magnetism to develop her knowledge for three-dimensional learning. Additionally, the study examines the challenges and facilitating factors that assisted the physics instructor to integrate three-dimensional learning into instruction. The instructor also investigated the pre-service science teachers' experiences with three-dimensional learning in developing knowledge domains. The guiding research questions are, as follows:

1. How can a physics instructor incorporate three-dimensional learning into planning and instruction of an undergraduate physics education course?
2. What type of experiences (positive or negative) does the physics instructor have in integrating three-dimensional learning into an algebra-based physics education course?
3. How do students perceive their experiences in learning through a three-dimensional framework?

Three-Dimensional Learning

In the United States, the K-12 science education framework (NRC, 2012) suggests that students learn science best through actively and collaboratively applying the content and practices into various scientific and socio-scientific contexts to make sense of complex phenomena and solve problems (Kaldaras et al., 2021; Nordine et al., 2019; Smith & Nadelson, 2017). In this framework, students are aimed to engage in discussions, analysis and interpretations of problems, evaluation and synthesis of procedures and arguments (Ford, 2015). Assessments serve as a form of evidence to make judgments about instruction and learning, in other words, to address the learning goals, instructional strategies, and learning approaches. These alternative evidence-based assessments can enhance focusing on active engagement and knowledge construction to address the demands of 21st century for scientific literacy (Next Generation Science Standards Lead States, 2013; NRC, 2012).

Focusing on the correct and certain answers forces learners to memorize the concepts in the form of discrete facts, but alternative assessment materials can focus on open-ended and contextualized questions to help students make connections among variety of ideas to develop complex knowledge. This requires moving the focus from reading textbook, solving end-of-chapter problems, cook-book type laboratories or step-by-step procedures towards integration of multiple investigations, which facilitate students' active participation through explanations in diverse ways such as journaling, student presentations, and questioning.

Krajcik et al. (2014) suggested that science learning required developing authentic scientific expertise to make sense of phenomena, design solutions to problems, and improve process skills. According to Krajcik et al. (2014), science teaching and learning included three dimensions including disciplinary core ideas (DCI), science and engineering practices (SEP), cross-cutting concepts (CCC) to develop coherence and interconnectedness to help learners think like a scientist. Three dimensions are related to each other to integrate phenomena-based learning with student-centered instruction to solve scientific and socio-scientific problems and understand the characteristics of science. **Figure 1** represents relationship between three dimensions.

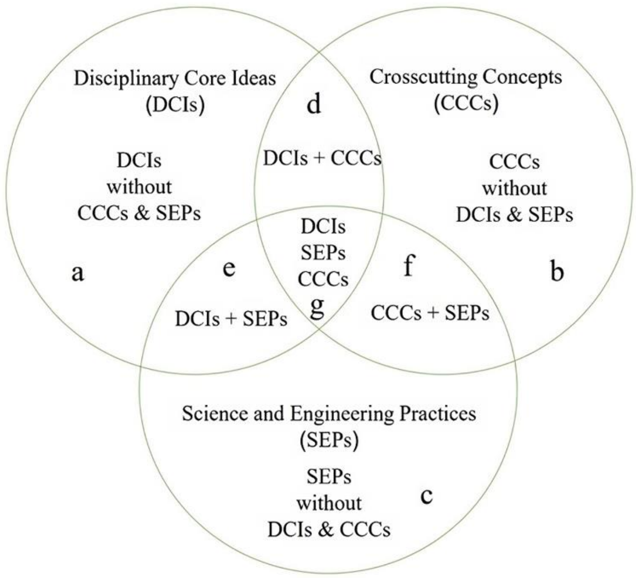

Figure 1. Model of three-dimensional learning (modified from NRC, 2012)

According to this model, Kaldaras et al. (2021) emphasized the significance of three-dimensional learning including SEP, CCC, and DCI to develop understanding of science ideas through application and explanation of phenomena and solution of problems related to real-life contexts. DCI were shown as part a on **Figure 1** to address the main scientific ideas in curriculum, instruction, and assessment including earth science, biology, life science, physics, physical science or chemistry. This part focused on the science content without inquiry practices and common science themes. For example, to explain the type of interactions, electric force can be explained by electric field to transfer energy through space. CCCs were shown as part b on **Figure 1** to define as common and relevant concepts in many disciplines and used to make connections across disciplines as bridges or tools through considering patterns, system and system models, cause and effect, structure and function, energy and matter. This part focused on common themes without disciplinary content and science process skills. In the case of interaction between the electric force and distance of objects, the cause-and-effect relationship aimed to be examined as an example of CCC. SEP were shown as part c on **Figure 1** to address the knowledge and skills necessary to do science through asking questions, conducting experiments, collecting and analyzing data, constructing models and explanations, and communicating results. This part focused on science process skills without referring to science content and common themes. As an example, understanding the relationship between electric force and distance between objects could be possible through investigating to collect and analyze data through reliable measurements. Combination of DCIs, CCCs, and SEP on the **Figure 1** was shown as part g to address the expectations of the three-dimensional framework in assessment and instruction. This combination could be stated, as follows: Students will be able to plan and investigate to explain that electric field exists between distant charges exerting forces on each other. This learning objective aimed to address SEP to focus on both product and process of the science through the following aspects of science: using variety of methods, empirical evidence, tentativeness, explaining natural phenomena through models, laws, and theories (Fanning & Adams, 2015). These practices were combined with cause-and-effect relationship as CCC to develop knowledge of electric force and electric field as DCI to refer to science as related to the natural and material world.

Moreover, other components of **Figure 1** aimed to integrate different aspects of the framework. For example, part d on **Figure 1** referred to combining science content with common themes: the influence of electric fields can be shown on charged objects to explore the cause-and-effect relationships within a system. Part e on **Figure 1** referred to combination of science content and SEP to emphasize science process skills with science content without connecting to common themes. For example, gravitational force between two objects could be investigated through engaging in an argument from evidence by supporting and refuting the claims. In another case, part f on **Figure 1** explained the combination of common themes and scientific inquiry. This part could be integrated through focusing on scientific inquiry as use of argumentation to support or refute claims with evidence and different energy forms without focusing on the science content.

Three-dimensional learning supports the use of inquiry-based instruction, problem-based learning, project-based learning, and discovery learning to promote students' abilities in engaging in scientific investigations, explanations, argumentation and modelling to make students responsible for their own learning to develop complex conceptual understanding (Nordine et al., 2019; Xiang et al., 2022). Three-dimensional learning is important to assist students in understanding what, how, and why questions within the process of thinking to make decisions and construct knowledge gradually. For example, Plummer and Small (2018) examined first grade students' three-dimensional learning in astronomy through the combination of planetarium fieldtrip and classroom lessons. Students constructed representations of the lunar phenomena and patterns. Analysis of students' representations showed that supporting classroom instruction with fieldtrips enhances students' engagement in doing science through understanding the changes in pattern and its function. In another study, Harris et al. (2015) discussed the role of project-based curriculum materials on sixth grade students' learning. There was a control group who studied on traditional textbook. Teachers in both groups received professional development on next generation science standards (NGSS) framework, but students who studied with project-based curriculum materials could engage in scientific practices along with disciplinary content and CCC.

METHODS

Action Research

Action research provides an opportunity for teachers to research their teaching (Taber, 2013). Action research is supportive to deal with the problematic situations or limitations of practice to make observations and reflections in trying new methods. Action research aims to improve the practice for different possible issues such as "poor student behavior, limited student understanding of a topic, lack of interest in a topic, poor quality homework, not enough student involvement in discussion, boys more engaged in practical work, etc." (McGregor & Woodhouse, 2015, p. 1). Action research aims to examine the process of teaching of a new procedure to improve the quality of learning and practice. Action research supports teachers to be metacognitive of their practices in ongoing cycles through questioning, e.g., What is the problem in action? How do I improve the situation? What will I do? What is the evidence to address the issue? (McNiff & Whitehead, 2012). Action research can shape the practice through collecting and interpreting data as evidence – such as tests, written essays etc.- to make conclusions about teaching and students' learning in a cyclical process.

Teacher reflective practice helps to develop strategies for different teaching and learning conditions to monitor, control, and regulate the teaching and learning processes in on-going cycles (Allas et al., 2020; Pintrich, 2002; Toom et al.; 2010). Altrichter et al. (2013) suggests that this process includes planning, teaching or doing, observing, and reflecting on the teaching practices in cycles. This metacognitive reflection activity is both personal and social meaning-making to learn from practice and experience: to relate various teaching and learning situations to teacher knowledge, teacher actions, and students' learning through being aware of students' alternative conceptions, predicting possible teaching situations, preparing thorough lesson plans, and responding to future experiences (Allas et al., 2020). This dynamic process can help teachers to be active and reflective through questioning, collecting and analyzing data, reflecting on, and evaluating their practice towards effective implementation of alternative and constructivist pedagogies.

Context & Participants

The first author, who is also the teacher-researcher, served as the participant and observer in this action research study. The researcher had worked in a physics laboratory for her master's degree for three years and attended the graduate school in science education program for five years. During her doctoral courses in the United States, the first author provided a direct account of the experiences and reflections on the problem or situation. K-12 science education framework (NRC, 2012) and NGSS (Next Generation Science Standards Lead States, 2013) suggest the implementation of three-dimensional framework, but most curriculum, textbooks, and teachers did not address the suggestions in the author's home country. She worked as a graduate teaching and research assistant while she stayed in the United States. After the author returned to her home country, she made observations on teaching and learning processes, and realized the need to integrate three-dimensional learning in teacher education courses. By reading the studies on three-dimensional learning such as Fanning and Adams (2015), Krajcik et al. (2014), Kaldaras et al. (2021), Nordine et al. (2019), and Plummer and Small (2018), the author could develop knowledge of three-dimensional framework. Also, while she was a graduate teaching assistant at an undergraduate physics laboratory, she could integrate inquiry-based instructional model to emphasize SEP (Sengul & Schwartz, 2020). In this new study, she aimed to plan to integrate a three-dimensional framework into her physics teaching. Teacher-as-researcher realized that teaching a physics course for pre-service teachers would be a good choice to address SEP, DCI, and CCC. The instructor chose to design a course on teaching electricity and magnetism to document her experiences and reflections in integrating NGSS framework. The instructor aimed to make a connection between what reform documents suggested and how pre-service science teachers experienced learning in a physics education classroom.

This action research study was conducted in an elective course for pre-service science and physics teachers focusing on teaching and learning on electricity and magnetism at a research university in the northwest region of Turkey. The course included four pre-service teachers: a master student in science education and three last-year pre-service physics teachers. The course lasted 12 weeks; the lesson had three-hour sessions each week. The class took place in a technologically enhanced environment or classroom including computers and hands-on materials.

Data Collection

Data collection in this physics education course focused on the topic of electricity and magnetism in four modules to understand the instructor's and her students' experiences. The author collected multiple sources of data during the Spring 2020 semester. These sources included instructor's lesson planning in 12-week period, pre- and post-lesson reflections, student artifacts, and students' reflections. The author aimed to provide the detailed descriptions of instructor's and her students' experiences with three-dimensional learning framework.

Table 1. Process of lesson planning for action research study

Module	Action research	
Electric charge & electric force Spring 2020 February 17-March 1, 2020	Plan	Focusing on the content, scientific practices, & crosscutting concepts
	Enact	- Observing interactions between charged and uncharged objects - Investigating charging of metals by contact through electroscope - Applying charge model to conductors and insulators - Explaining polarization and attraction between charged objects
	Observe	- Students had difficulty in conducting experiments through some metals, insulators, & electroscope. - Students tended to explain how differently charged objects could interact without making observations. - Science content was easy to understand, students needed experience to make observations about physical interactions.
	Reflection	- I should integrate and emphasize scientific practices. - Activities should be selected appropriately to address the three-dimensional learning. - Crosscutting concepts were not emphasized sufficiently.

Instructor lesson planning

In the 12-week period, the instructor divided the course content into four modules: Three weeks of the course addressed electric charge and electric force, next three weeks of the course focused on electric field and electric potential, next three weeks of the course were related to electric circuits, and the last three weeks of the course focused on magnetism. The physics instructor prepared lesson plans following the action research cycle to plan, enact, observe, and reflect on what happened and what needed to be done for four modules (Altrichter et al., 2013). An example of action research plan for the first module was provided on **Table 1**. **Table 1** showed that before the instruction, the instructor explained the planning of the lesson; after the instruction, the instructor made observations and reflections on the enactment and students' learning. The lesson planning in each module was utilized to modify implementation of the second module and use the feedback to make changes in the third and fourth modules.

Instructor pre- & post-reflections

The instructor wrote reflective journals before and after the instruction. The instructor's reflections focused on the strengths and challenges of preparing and implementing the lesson plan and students' learning process. These journalling process guided by the following questions (Etkina, 2010; Sengul & Schwartz, 2020): What were the instructor's goals for the lesson? How did the instructor achieve these goals? What instructional strategies did the instructor use? What forms of assessments did the instructor prepare? What were the strengths and weaknesses of the lesson before and after the lesson?

Lesson artifacts

Lesson artifacts were collected to analyze the lesson content, students' worksheets, and students' lesson plans. Students worked on laboratory activities for each module, and these worksheets were examined by the instructor for possible student difficulties. In addition, at the end of the course, participating students prepared lesson plans and questions for one of the modules to develop knowledge of student learning, instructional strategies, and curriculum. The lesson plans followed the suggestions of Loughran et al. (2006) for preparing content representations (CoRes) to answer the guiding questions: What do you intend students to learn about the idea? Why is it important for students to know this idea? What else do you know about this idea? What difficulties/limitations connected with teaching this idea? What do you know about students' thinking? Which teaching procedures do you aim to use? What specific ways do you use to understand student confusion?

Student reflections

Students reflected on their learning experiences with three-dimensional instruction during the course. Students responded to the following sample questions: What are your goals for teaching this topic? Was this course/lesson helpful? Why? How does this course change your perceptions towards science?

Data Analysis

Data analysis was conducted via constant comparative method (Corbin & Strauss, 2008): the coding process started by using theory-based and emergent-codes to compare in the process of category and theme development in an iterative and cyclic process referring to three-dimensional framework. Triangulation techniques were used to understand the instructor's experiences. The instructor's reflections, lesson plans, and lesson artifacts (including worksheets and student reflections) were coded using in-vivo or descriptive coding to organize the data and find frequent codes to classify them based on the common themes. The students' reflections and lesson artifacts were also used to understand their experiences within course context.

Table 2. Three-dimensional learning plan for electricity/magnetism (Next Generation Science Standards Lead States, 2013)

Module	Three-dimensional learning		
Electric charge & electric force	HS-PS2-4 Use mathematical representations of Coulomb's law to describe & predict the electrostatic forces between objects. HS-PS2-6 Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.		
	DCI	SEP	CCC
	HS-PS2: Motion & stability: Forces & interactions - PS1.A: Structure & properties of matter - PS2.B: Types of interactions	Use of mathematics & computational thinking Obtaining, evaluating, & communicating information *Nature of science: Science models, laws, mechanisms, & theories explain natural phenomena*	Patterns Structure and function
Electric field & electric potential	HS-PS3-1: Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other components and energy flows in and out of the system are known HS-PS3-2: Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motion of particles (objects) and energy associated with the relative position of particles (objects)		
	DCI	SEP	CCC
	HS-PS3: Energy - PS3.A: Definitions of energy - PS3.B: Conservation of energy & energy transfer	Using mathematics & computational thinking Developing & using models	System & system models Energy & matter *Nature of science: Scientific knowledge assumes an order & consistency in natural systems*
Electric circuits	HS-PS3-5: Develop and use a model of two objects interacting through electric fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction		
	DCI	SEP	CCC
	HS-PS3: Energy - PS3.C. Relationship between energy & forces	Developing & using models	Cause-and-effect
Magnetism	HS-PS2-5: Plan and investigate to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current.		
	DCI	SEP	CCC
	HS-PS2: Motion & stability: Forces & interactions - PS2.B: Types of interactions	Plan and carry out investigations	Cause-and-effect

RESULTS

Theme-1: Integrating Three-Dimensional Instruction into Physics Education

The three components, SEP, DCI, and CCC of three-dimensional learning were embedded into physics instruction in different ways through different instructional strategies. Instructor commented on her work on planning a three-dimensional lesson and stated:

> I realized that most pre-service physics teachers in Turkey were not familiar with the use of scientific practices along with DCI. They were used to learn the content and solve multiple questions through derivative and integral calculations from introductory physics courses. They were not ready to teach in a high school or middle school classroom, so I aimed to plan a course to help pre-service teachers have experiences in three-dimensional learning in an algebra-based physics course (pre-lesson reflection).

How were the instructional methods and activities appropriate to enact the three-dimensional framework? The instructor preferred reading NGSS to categorize the framework for the specific content, electricity and magnetism. The articles were read to understand the characteristics of the framework, and the physics textbooks were checked to classify the modules in an appropriate order. The instructor planned the course considering NGSS model and prepared learning objectives and teaching strategies to address the reform suggestions.

Table 2 presents how the tenets of three-dimensional learning were aimed to be integrated into instruction in the first cycle of preparation as suggested by NGSS.

The instructor used **Table 2** as a guide for the lesson planning.

Table 3. Learning objectives & instructional strategies for course

Module	Learning objectives: Students will be able to	Instructional strategies
Electric charge & electric force	- Describe charge model in conductors and insulators - Explain polarization, attraction, and repulsion for charged and uncharged objects - Use Coulomb's law and superposition principle for electric forces	- Argue about a phenomenon: Playground problem - Hands-on experiment with various materials. - Analyze data from an experiment - Multiple-choice & open-ended questions
Electric field & electric potential	- Visualize electric field in terms of source & test charge - Explain the motion of charged particles in electric fields. - Establish the relationship between electric field, electric potential, and electric potential energy - Compare electric field diagram for point-like charges & capacitors	- Argue about a phenomenon: Van der Graff & photocopy machine - Modelling: Visual, graphical, & mathematical - Solving conceptual questions - Multiple-choice questions
Electric circuit	- Construct a concrete model of current flow through conductors - Explore conductivity and resistivity properties of metals as charge carriers to explain resistance and Ohm's law - Apply Kirchhoff's laws to analyze parallel & series circuits - Investigate energy transfer & power dissipation in circuits - Analyze complex circuits including multiple resistances and capacitors	- Argue about a phenomenon: Human circulatory system, & home appliances - Modelling: Visual, analogy, diagram, & mathematics - Analyze data from an experiment. - Analyze complex circuit diagrams. - Solve conceptual & multiple-choice questions
Magnetism	- Explore basic magnetic phenomena: Magnetic poles, magnetic forces, torques, & magnetic fields due to currents in wires, loops, & solenoids, motion of charged particles in magnetic fields. - Explore the theory of electromagnetism to the phenomena of permanent magnet through a current loop - Explain the atomic model of ferromagnetism - Apply electromagnetic induction in different situations	- Argue about a phenomenon: Motion of protons in earth's magnetic field & mass spectrometer. - Modelling: Visual, mathematical - Video experiments & demonstrations - Solving conceptual questions - Multiple-choice questions

Table 3 was developed in the second cycle of the preparation while planning the learning objectives and learning tasks for the lesson. These learning tasks included the activities integrated in the instruction. For example, in parallel to suggested scientific practices by NGSS, the instructor assisted students to engage in an argument about a real-life phenomenon such as photocopy machine, human circulatory problem to engage in hands-on or virtual experiments, data collection and analysis, modelling, scientific explanations, and mathematical calculations. Besides, aspects of nature of science were also emphasized in parallel to CCC and SEP within the lesson. Emphasis on scientific practices and CCC along with DCI made the instructor aware of how pre-service teachers engaged in three-dimensional learning in different ways.

During the preparation of course materials, the instructor wrote reflections to explain the process of planning a three-dimensional lesson. The instructor focused on how to emphasize the characteristics of three-dimensional framework through focusing on SEP, DCI, and CCC. Reflections guided the instructor in determining the type of activities. The instructor stated:

> While planning the first module, I thought that combining electric charge and electric force concepts together would be a good idea to address the standards and teach "forces and interactions" with a subtitle as "structure and properties of matter." Students need to understand the type of the materials and their interaction with other objects, they will also need to consider the polarization during the interactions. Students do hands-on experiments and model abstract phenomena. This will give a holistic idea when students think about both the content, practice, and patterns across interactions (pre-lesson reflection).

After the first module, the instructor realized pre-service teachers' capacity to work on visuals and simulations, so integrated more visual resources to make students think and explore. The second module focused on definition and conservation of energy as a core concept and CCC to understand the relationship among electric field, electric potential, and electric potential energy within a system of particles. The third module emphasized the relationship between energy and forces through complex electric circuits to explain the cause-and-effect relationships. The fourth module addressed the type of interactions in motion concept to explain how electric current and magnetic field interact with each other. The instructor's experiences in the design and implementation were presented in the second theme.

Theme-2: Physics Instructor's Experiences & Insights

It was important to develop literacy for standards-what the standards tell us about the implementation of scientific practices, CCC, and DCI to prepare the learning objectives and instructional units. Turkish Education does not have a curriculum or textbook addressing three-dimensional learning framework. The instructor aimed to align the instruction to address NGSS. The instructor stated:

> Teachers usually expect to be given the curriculum to use in the classroom. Although they are not educated to be curriculum developers, they should know how to prepare formative and summative assessments that address not only content competency but also learners' cognitive and social development through SEP and CCC that are common concepts in all science fields. Pre-service science teachers need examples of different types of assessments to integrate in their lesson plans as part of the implementation of a three-dimensional framework. My aim is to help them align the assessments with the framework, and it will be an iterative process to check whether we are addressing the expectations of the standards (post-lesson reflection).

Pre-service science teachers were used to solving problems on electricity and magnetism with only mathematical calculations, and they were not used to working on conceptual problems or making scientific explanations. The differences between what they expected and what they were expected made them aware that they should focus on scientific inquiry and students' learning including metacognition, active involvement, sharing, and responsibility. After making the pre-service teachers became aware that the lesson content should become more conceptual, the instructor focused on evaluating how the characteristics of the course aligned with NGSS:

> NGSS provided me with good support for the implementation of framework. This outline helped me prepare learning outcomes for each module to plan and design the lesson tasks for pre-service teachers' learning of the framework. It is like a backwards design to help learners investigate in the lesson to answer overarching questions. The use of scientific practices such as communicating information, developing and using modeling, planning and carrying out investigations along with use of mathematical thinking guided students to enhance their voice and adapt to new learning contexts. However, CCC were new to students. Although I integrated patterns, system and system functions, and cause-and-effect relationships in the investigations or classroom activities, they were implicitly emphasized, and students had difficulty in integrating them in their own lesson plans (post-lesson reflection).

Teaching through a three-dimensional framework automatically guided the instructor to shift the learning process from traditional to constructivist inquiry. Pre-service teachers realized that they should prepare assessments for doing science rather than rote learning to figure out what, how, and why something happened. The investigations during the course also guided pre-service teachers to collect and analyze data to answer questions related to daily-life phenomenon and make scientific explanations rather than verifying the formulas.

Three-dimensional learning took time for preparation; the electricity and magnetism topic provided us a series of connected modules to talk about different research questions such as "How does Coulomb law describe and predict electric forces between objects? How does electric current produce magnetic field or changing magnetic field produce a current?" Although scientific practices and DCI were explicitly integrated in the instruction, the integration of CCC were implicit and not emphasized. The instructor added:

> Another challenge was related to the integration and emphasis of characteristics of nature of science; aspects of science were implicitly addressed during the instruction. In the first module, our discussion focused on scientific laws, it was related to scientific practices. However, I did not emphasize the difference between models, laws, and theories in scientific work. In the second module, science was defined as assuming order and consistency in natural systems, but in parallel to CCC such as system and system functions, this characteristic of science was not emphasized. In addition, I really wonder, different from the suggestions of the framework, could I integrate other aspects of science in the course? (post-lesson reflection).

As a teacher educator, the instructor realized that she should have emphasized not only the content and scientific practices but also CCC and nature of science explicitly. The instructor thought that college science classes and national curriculum were content focused to emphasize traditional instruction; therefore, Turkish education system had produced individuals focusing on the results rather than process.

Using a three-dimensional framework could act as a guide to help pre-service teachers design lesson plans to address the scientific process skills and characteristics of science besides the content to teach. The important point was professional development, how can teachers tend to change their current practices? The instructor stated:

> I was very worried that the pre-service teachers might not accept the suggested practices. The course served as a professional development for

> them to change their traditional practices on teaching and learning electricity and magnetism. In the teacher education program, they develop knowledge of scientific inquiry, scientific practices, and nature of science. However, they do not have enough opportunity to integrate their knowledge into practice. This shows that teacher education requires more attention on NGSS training in science education (post-lesson reflection).

The instructor realized that teacher training for three-dimensional framework was not enough for only one course design. Pre-service teachers should engage in professional development to plan lessons through embedding three-dimensional learning including content activities, experiments, and discussions on different aspects of science.

These plannings and course materials for the course made the instructor have negotiations between content knowledge to teach electricity and magnetism and knowledge for three-dimensional framework or NGSS. The instructor stated:

> Designing a course to integrate NGSS was new to me, but it enhanced my awareness to teach not only for the content, but to make pre-service teachers realize and embed scientific practices and CCC into planning. I was able to integrate phenomenon-based activities or problems such as the working principle of a photocopy machine or Van der Graff machine. It was hard to think of the lesson as a whole or holistically, but I was able to change pre-service teachers' tendency to design lesson plans. Developing and using models, planning and carrying out investigations, use of mathematics were the scientific practices to think with patterns, cause-and-effect relationships, and system and system functions. This course guided the students to develop these competencies (post-lesson reflection).

Another challenge of teaching three-dimensional framework in Turkey was student approach to a new type of teaching and learning. The instructor stated:

> My concern was related to whether pre-service teachers would accept this teaching format or drop the lesson. I was lucky that four pre-service teachers attended the course throughout the semester and left the class with positive reflections (post-lesson reflection).

The instructor's reflection showed her confidence in teaching a course with a three-dimensional framework. Students' positive reflections made the instructor evaluate students' work during the course.

Theme-3: Students' Perceptions of Three-Dimensional Learning

Four pre-service teachers also wrote reflections and referred to their experiences as focusing on more conceptual physics rather than mathematics knowledge. They had conceptual difficulties on the subject since they used to memorize the formulas. For example, student-1 stated:

> The course focused on assessing conceptual knowledge rather than procedural math knowledge. I did not have to remember any formulas. But as a teacher candidate, I have difficulty in remembering concepts from high school. I see that it is not enough to know a formula, we need to get the logic behind it, we need to have higher-level thinking skills (student reflections).

To develop students' conceptual understanding and knowledge of student conceptions and instructional strategies, students worked on CoRes construction for each module. One of CoRes on magnetism module was presented in **Table 4**.

Table 4 shows the student preparation of CoRes on magnetism topic referring to why the content was taught and possible learning difficulties. Students' preparation of CoRes for each module helped them present components of their knowledge for teaching and learning electricity and magnetism. The instructor was also able to see the enhanced interest in students' approach to work on CoRes. At the end of the course, students reflected on their learning experiences and student-1 stated:

> At the beginning of the semester, I felt that I was incomplete. I was having trouble with some topics. Now, I feel better about them. I believe weekly assignments and unit plan were beneficial to become a teacher. I have a more complete picture of electricity and magnetism. I improved my conceptual knowledge about electricity and magnetism. I now know common misconceptions and difficulties on the topic. We should use inquiry-based instruction in teaching this topic, not lecturing. Students should take an active role in class; teachers should be a guide and role model for students (student reflections).

The student explained how his fear and doubt turned to satisfaction and confidence in teaching and learning electricity and magnetism. Another student, student-2 addressed the role of scientific method in teaching and learning science and stated:

> Students should develop and test hypothesis by using scientific methods including data collection, interpretation, technology integration, simulation.

Table 4. An example of CoRes from students' work

	IDEA-A	IDEA-B
What you intend students to learn about idea	I want students to know: • Magnetic poles are not same as electric charges. • Magnetic forces & electric forces are different. • A compass needle is like a small bar magnet. • Magnetic characteristics of the Earth. • A compass' orientation is used to determine direction of magnetic field & geographic direction • How to draw magnetic field lines.	• How to calculate magnitude of magnetic field & magnetic force on various situations. • How charged objects behave in magnetic field. • What magnetic flux is & how to calculate it. • What Lenz's law is. • What Faraday's law is. • How to calculate induced current • Right hand rule.
Why is it important for students to know this	• We use magnetism to create electrical energy. Most of energy that we use comes from rotating magnets.	To make sense of what is going on around us, it is important to know electromagnetism.
What else do you know about this idea	• Gauss's law for magnetism • Biot-Savart law	• Ampere's law • Maxwell's equations
Difficulties/limitations connected with teaching this idea	Misconceptions (Knight, 2004): Students may think that • We can separate the poles of a magnet. • If one end of a bar magnet attracts a paper clip, the opposite end will repel the paper clip. • Electric and magnetic fields are interchangeable. • Electric charges & magnetic poles are equivalent. • The induced field opposes the applied field itself rather than opposes the change in the applied field. • Electromagnetic induction is due to motional EMF.	Student's difficulties and limitations • Most students have never experienced repulsive force between two magnets. • Students are not familiar with electromagnets. • They do not know vectors cross product yet. • Since it is an abstract concept mostly, there is a need to visualize situations like motion of particles in magnetic fields in 3D.
Knowledge about students thinking, which influence your teaching of this idea	• Force between two magnets is an abstract concept. Description of basic concepts is not enough. • Observation & hands-on activities are necessary. • Starting with Oersted's discovery & then magnetic field around a wire & then right-hand rule.	
Other factors that influence your teaching of this idea	• Pre-mature math knowledge • Misconceptions & problems students have about electric field	• The physical settings of the school (access to internet, laboratory…) would be a factor blocking learning
Teaching procedures	• Talk about dipole model, forces, & torques on them. • Compass needle, test charge analogy for electric field. • Define magnetic field through Oersted's discovery, magnetic field around a wire, right hand rule. • Hands-on experiences • Using a compass to show how it orients around a current-carrying wire.	• Magnetic flux: Using analogies • Introducing Lenz's law before Faraday's law, makes students reason about induced currents. • Inquiry method is the most proper method for the topic. • Before going into numerical problems, asking conceptual questions first is more helpful.
Specific ways to understand student confusion	• Predict-observe-explain activities • Simulations and some visuals to support learning	• Do-at-home exercises indorse learning • Post-test to assess student learning

> Developing science process skills, scientific method. I believe that students should first learn how science works. I have learned that conceptual understanding is more important through inquiry and scientific methods. Research questions, data collection, data analysis, and testing hypothesis are the main points … I can ask conceptual and open-ended questions to understand how students think (student reflections).

DISCUSSION & IMPLICATIONS

Integration of three-dimensional learning was a key suggestion of reform documents to enhance the use of constructivist pedagogy, to improve learners' engagement with 21st century skills and to emphasize the role of science in society (Next Generation Science Standards Lead States, 2013, NRC, 2012).

Using a three-dimensional framework provided the instructor with an organization to identify the standards for specific learning outcomes. The instructor developed the course materials to address the expectations of constructivist pedagogy to emphasize learning by doing science. This process helped the instructor realize that scientific practices and DCI were combined to teach a concept, and how these practices and core ideas were connected to instructional practices. Krajcik et al. (2014) suggested that three dimensions of the framework provided coherence in developing scientific expertise and enhancing learners' engagement in data collection, analysis, evaluation, and synthesis. Conducting action research supported the instructor to plan, teach, reflect, and learn in a cyclic process to develop that coherence in her teaching. The pre- and post-reflections assisted the instructor to reflect on her lesson planning and teaching to evaluate whether learning objectives were achieved during the instruction. The instructor found that it was easy to combine SEP and DCI with the appropriate instructional strategies. However, emphasis on nature of science and CCC was lacking and implicit since the instructor mostly focused on active participation. This study showed the value and significance of having a strategic approach to change teaching practices and to enhance reflective instructional approaches. The lesson planning guided the teacher-as-researcher to develop knowledge of how to implement three-dimensional framework and assist pre-service teachers to learn the development of teaching resources. The products of instructor's and pre-service teachers' lesson planning made them aware of different components of an instructional process and developed their confidence in becoming a teacher.

Recent reform efforts strongly recommend not only cognitive aspects of learning but also social and epistemic practices to be integrated in classroom instruction (Duschl, 2008; NRC, 2012; Next Generation Science Standards Lead States, 2013). Three-dimensional learning addresses these recommendations and requires teachers' professional development to develop complex knowledge structure of PCK (Shulman, 1986; Smith & Banilower, 2015). According to Shulman (1987), effective teaching required teachers to focus on multiple elements of an instruction including content, pedagogy, curriculum, learners and learning, contexts of schooling, educational philosophies, goals, and objectives. Berry and Milroy (2002) argued that science teaching expertise represented teaching practices, use of experimentation and modelling to address students' learning challenges, make adaptations based on learners' needs, and develop scientific conceptions. Teachers need to know what to teach and how to teach specific content with specific strategies, procedures, representations, and language of science to facilitate active student participation to learn through inquiry and construct scientific knowledge. Teachers need to develop knowledge of not only content and pedagogy but also scientific practices, CCC, and nature of science (Osborne, 2007). Future work should focus on aspects of three-dimensional instruction to develop PCK for scientific practices or CCC.

Action research can be a strategy to help pre-service and in-service teachers realize what they know about and how they can successfully integrate their knowledge into practice. The instructor had knowledge of scientific practices, subject matter knowledge, and pedagogical knowledge. When a teacher possesses knowledge of subject matter knowledge such as physics and pedagogical knowledge to teach the concepts, the teacher holds PCK for physics topics to address the students' conceptions and instructional strategies. How about scientific inquiry or scientific practices? In this action research study, the instructor was able to make connections between knowledge of scientific practices, subject matter, CCC along with pedagogical strategies and students' conceptions even though the instructor emphasized some aspects of three-dimensional framework such as CCC implicitly. Sengul et al. (2020) studied in-service science teachers' PCK of argumentation as a scientific practice and explored teachers' knowledge of argumentation, in particular, claim, evidence, and justification for student conceptions and instructional strategies. In another study, Krajewski and Schwartz (2014) studied a biology instructor's PCK of NOS development through action research. The authors suggested that there was an overlap and a connection across teacher knowledge domains: teachers should not separate NOS from subject matter and pedagogical knowledge, but teachers should understand the connections between knowledge of NOS, subject matter, and pedagogical knowledge. They suggested that PCK for NOS was related to teachers' knowledge of NOS, pedagogical knowledge, and subject matter knowledge considering knowledge of learners, assessment, curriculum, and context. In other words, when teachers teach lessons with a three-dimensional framework, they need to consider student conceptions, instructional strategies, assessment etc. separately to establish the coherency across the dimensions of scientific practices, DCI, and CCC.

The instructor in this study could use the advantages of doing action research to make modifications in the instruction, assessment, and curriculum to make connections between different knowledge domains. This reflective practice gave several opportunities:

(1) to design a course with backwards design that the learning outcomes were determined at the beginning of the lesson (Wiggins & McTighe, 2005),

(2) to develop formative and summative assessments to address the expectations of NGSS and learning objectives,

(3) to reflect on the instructional processes and students' learning to understand the strengths and weaknesses, and

(4) to explore students' learning experiences with three-dimensional learning.

Action research served as a facilitating approach for the implementation of new instructional strategies and frameworks.

Feldman and Bradley (2019) argued that action research supported teachers-as-researchers to develop a critical eye on problematic situations or implementation of new approaches through questioning, reflection and communication. In this process, teachers act in ongoing cycles through planning, acting, observing, and reflecting to problematize the situation, initiate a change in practice, and provide feedback on what happened (Capobianco et al., 2020). Teachers' critical reflections can change their practices and beliefs about teaching, learning, and science. The instructor in this study started to think about having a holistic approach in designing a course and lesson plans since knowledge of scientific practices or CCC or NOS was related to other knowledge domains and should be considered together in planning assessments.

Teacher change is difficult to initiate, but teachers can be given freedom and responsibility to conduct their own research in their classroom. Action research serves as a guide for in-service and pre-service teachers as well as for college instructors to address the problems in their practice and to make changes in the instruction, curriculum, and assessment. Action research can help science teacher educators to facilitate discussions on the implementation of NGSS. Teachers need to develop a metacognitive approach to their work to understand what happened and why and how something happened to try to change their practices and students' learning experiences. Further research should focus on teachers' enactment of three-dimensional framework in different contexts and disciplines to understand changes in teacher thinking and practices.

CONCLUSIONS

These findings showed that the use of three-dimensional frameworks as a model to plan the instruction helped the instructor design learning objectives specific to science content, inquiry, and common themes. This method of planning and instruction was helpful to design learning materials aligning curriculum, instruction, and assessment with the constructivist pedagogy. The instructor was able to integrate SEP with the science content, but there was implicit implication of CCC; the instructor rarely emphasized CCC during the instruction. The lesson planning for action research guided the lesson implementation and promoted instructor's reflections to make modifications. Three-dimensional learning model supported instructor's focus on not only science content, but also pre-service science teachers' engagement with 21st century skills including adaptation, scientific communication, collaboration, and use of technology. This process required science teachers to develop knowledge of scientific inquiry, knowledge of content, and knowledge of CCC. This result emphasized the need for further research to focus on teachers' knowledge of specific science practices, nature of science, or assessment. Action research in this study was helpful to examine the physics instructor's and her students' experiences in teaching and learning through three-dimensional learning. These research studies can reveal teachers' approaches to implement new strategies and reflect on their practices for improvement.

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