Simulation-Based Instructional Materials on Central Dogma of Molecular Biology

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Abstract

The essence of Genetics lies in the understanding of the concepts of Central Dogma of Molecular Biology. Although these ideas are fundamental to the field, they are notoriously difficult to understand and visualize. While simulation-based instructional materials are found to improve the teaching-learning process in science education, little has been done to assess their effectiveness in teaching and learning the concepts of Central Dogma of Molecular Biology. Hence, this study aimed to examine the effectiveness of simulation-based instructional materials towards the learning performance of Grade 12 learners on the concepts of Central Dogma of Molecular Biology. This study utilized a mixed-method approach. Adapted computer simulations were properly integrated in the developed session plans. Pretest and posttest were conducted, and results showed that the learners demonstrated improvement from approaching proficiency to advanced mastery level on the concepts of Central Dogma of Molecular Biology. Furthermore, it was revealed that the learners' pretest and posttest mean scores on the concepts differed significantly ($p<.05$). The result of the semi-structured interview revealed that the learners were engaged in experiential learning using simulation-based instructional materials.

Keywords: *Central Dogma, computer simulations, genetics, instructional materials, Molecular Biology*

Introduction

The COVID-19 pandemic has ushered educational institutions across the globe to new technology-based modalities of instructional implementations (Dukes, 2020; Mahaffey, 2020; Masoud & Bohra, 2020). The changes in the educational landscape posed constraints to teachers with the emergence of new technological challenges and instructional strategies (Sunasee, 2020) in teaching science concepts that have highly abstract mechanisms (Arrieta, et al., 2020; Huang, 2020), such as Genetics. Genetic education is considered necessary in schools to develop learners who can understand issues on the applications of Genetic technologies (Change & Anderson, 2020).

However, the essence of Genetics lies in understanding the concepts of Central Dogma of Molecular Biology. Understanding this topic at the secondary level is essential and a precursor to other higher concepts in biology as it connects biological processes happening at the cellular and organismal levels (Picardal & Pano, 2018). While this topic is regarded as core to the discipline, many teachers and learners are facing the burden of understanding its highly abstract concepts. Hence, it remains difficult to teach, and least mastered among teachers and learners, respectively (Wright et al., 2014). Many authors pointed out that this is due to the complexity of the topic's underlying concepts that are not available for direct observations (Change & Anderson, 2020; Picardal & Pano, 2018; Reddy & Mint, 2017).

Consequently, science education in the Philippines has shown downward trends as observed in national and international standardized assessments (Adarlo & Jackson, 2017; Department of Education, 2020). Rivera (2017) posited a need to develop robust teaching pedagogies to elevate the country's scientific literacy by devising innovative teaching techniques, such as integrating technology-based instructional tools in the teaching-learning process. Likewise, Huang (2020) pointed out that using appropriate technology-based instructional materials to support the teaching-learning process in the COVID-19 pandemic is deemed necessary to mitigate its educational constraints.

Simulation-based instructional materials are commonly used in science education to promote active learning. These learning materials are found to scaffold learners to understand concepts that require higher abstract thinking by providing linkages between what is heard and what is seen (Olga et al., 2020). More senses are involved; hence, learners become more engaged in deep learning that empowers understanding as opposed to surface learning. Despite the advantages offered by simulation-based instructional materials in science education, many teachers are encumbered, and have no bold attempt to integrate these tools in their teaching pedagogies. Anoba and Cahapay (2020) pointed out that the inaccessibility of resources and the lack of competence and confidence in the proper utilization of technology are among the reasons. Hence, these available simulation-based instructional materials are not maximized, and little has been done to assess their effectiveness in teaching and learning the concepts of Central Dogma of Molecular Biology. This prompted the researchers to conduct a study to assess the effectiveness of simulation-based instructional materials on the learning performance of Grade 12 learners in Central Dogma of Molecular Biology.

Objectives

This study aimed to assess the effectiveness of simulation-based instructional materials on the learning performance of Grade 12 learners in Central Dogma of Molecular Biology. Specifically, this study sought to answer the following questions:

1. What are the mean mastery level scores of the learners in Central Dogma of Molecular Biology before and after the conduct of the study in terms of: a) DNA Replication, b) Transcription, and c) Translation?
2. Is there a significant difference in pretest and posttest scores of the learners in Central Dogma of Molecular Biology in terms of: a) DNA Replication, b) Transcription, and c) Translation?
3. What are the attitudes of the learners exposed to simulation-based instructional materials?

Review of Related Literature

Simulation-Based Instructional Materials

With science and technology developing rapidly, science education is now presently taught using several methods, techniques, and models to improve learning. DeCaporale-Ryan et al. (2016) attest that helping learners build representations of complex structures by integrating words and pictures is one way to improve learning. Moreover, this method has aided the development of a unique category of immersive educational tools called simulation-based instructional materials (Kutz et al., 2016).

Gruler et al. (2019) define simulation-based instructional materials as artificial representations of real conditions. These are instructional tools that can provide learners with a safe and supportive setting and allow them to practice more abstract and critical thinking skills while eliminating any danger through active learning. Compared to traditional classroom discussions, these tools can also generate their interests, providing insights through experiential learning (Juan et al., 2017).

Likewise, Cant and Cooper (2017) established that simulation-based instructional materials could develop and improve learners' critical, strategic thinking, and creativity skills. Prior studies have also emphasized that simulations are effective in creating scenario-based environments for learners to interact and apply their knowledge and skills to deal with issues of the modern world, and for teachers to accomplish their objectives (Angelini, 2016; Becker & Hermosura, 2019; Juan et al., 2017; Kutz et al., 2016). Cai et al. (2016) attest that these simulations enable learners to experiment interactively with concepts' essential theories and applications. Furthermore, they can provide reliable and instant feedback and give learners opportunities to try out different variables and instantly evaluate their ideas for accuracy.

On the contrary, the disadvantage of simulations is that they restrict learners' ability to explore new information, which is determined by the number of simulations accessible for a given subject. According to Efe and Efe (2011) and Lameras et al. (2016), the utilization of computer simulations greatly depends on their availability and compliance with curricula, and teachers' efficacy in using them. Recent studies have shown that the characteristics of these computer models (e.g., technical, content, instructional qualities) must be emphasized in order to ensure that the learning, imagination, decision-making, coordination, reasoning capacity, and initiative of the learners are all positively impacted (DeCaporale-Ryan et al., 2016; Gunda & Dongeni 2017; Mceneaney, 2016; Olga et al., 2020).

The Learning Process in Simulation-Based Instructional Materials

The learning process is not guaranteed through the knowledge and intelligence of the teacher alone. According to Lameras et al. (2016), teaching must be coupled with appropriate selection and use of instructional resources and teaching strategies. Therefore, in order to optimize the learning process, appropriate and effective teaching style and instructional materials such as computer simulations should be planned consciously.

As cited by Pugh et al. (2020), John Dewey posited that continuous teaching by learning through doing leads to changes in learning. Likewise, David Kolb, as cited in Reshmad'sa and Vijaya Kumari (2017), noted that reflection is an important aspect of the learning process and that learners must consciously participate in the process through experience.

Similarly, Juan et al. (2017) commented that simulation-based instructional materials are tools that can engage learners in experiential learning. By using computer simulations, learners are actively involved through participating in realistic, dynamic, and complex situations. Pugh et al. (2020) emphasized that in order to remain involved in learning, learners should focus on what is happening before and during an activity. When learners take a thoughtful approach focused on actual or virtual knowledge, it can lead to increased strategic thought and, as an effect, a stronger comprehension of concepts (Cant & Cooper, 2017).

According to Kolb's (1984) experiential learning theory, learners learn in four stages: *concrete learning,* where they have a new experience; *reflective observation*, where they reflect on their experience personally; a*bstract conceptualization*, where they form new ideas or adjust their thinking based on the experience and their reflection on it; and *active experimentation*, where they apply new ideas to the world around them. Kolb argues that effective learning is seen as the learners go through the cycle, and they can enter into the cycle anytime (Reshmad'sa & Vijaya Kumari, 2017). As a result, the learners can improve by problem-solving and achieving a higher understanding of the concepts. On the other hand, Pugh et al. (2020) stressed that the human learning method could involve a variety of time periods based on what is to be processed and how rigorous the process is.

The Central Dogma of Molecular Biology

The Central Dogma of Molecular Biology is a vital topic in Genetics. It is the key to understanding how the deoxyribonucleic acid (DNA) information is used to produce functional proteins. Understanding the Central Dogma of Molecular Biology at the secondary level is essential and a precursor to the higher concepts in biology and other fields of Science (Wright et al., 2014) to be able to connect the process to the activities happening at the level of cells, organs, and organisms (Newman et al., 2012; Van mil et al., 2013).

Accordingly, Change and Anderson (2020) reported that although learners have correctly used the terms such as transcription and translation processes, they still failed to explain the canonical model of DNA to RNA to protein. Molecular basis of inheritance is cited to be a difficult topic even for the biology senior learners (Picardal & Pano, 2018) because of the underlying concepts that are at the molecular level and are not available for direct observations of the learners (Change & Anderson, 2020; Reddy & Mint, 2017; Wright et al., 2014).

Likewise, connecting the ideas of genes and their protein components, as well as protein products and phenotype, has proven to be especially difficult for learners (Wright et al., 2014). One reason for this challenge is that Genetics definitions span many organizational layers (Change & Anderson, 2020) and require learners to comprehend that the physical constructs of DNA comprise information (Picardal & Pano, 2018). Learners must first consider the interactions between DNA, mRNA, and proteins, and then those between protein functions and diseases, in order to understand the principles connected with the Central Dogma of Molecular Biology and, finally, Genetics. Learners must consider why the genetic code uses three consecutive nucleotides for each codon, why start and stop codons are used, what promoter regions are for, and how genetic mutations influence phenotype, induce disease, and form the basis for variation (Change & Anderson, 2020). However, these ideas were observed to be challenging for learners to understand.

To date, several recommendations have been made on how to promote learning of the subject more effectively. For instance, some activities have included learners manipulating different molecular components and processes utilizing computer animations (Marbach-Ad et al., 2008; Rotbain et al., 2008), while others have involved learners physically modeling the processes under review (e.g., Marshall, 2017; Takemura & Kurabayashi, 2014). Takemura and Kurabayashi (2014) used a role-playing game with physical props to teach transcription and translation, while Marshall (2017) used a paper-modeling activity to replicate molecular processes with undergraduate Genetics learners. These studies highlight that in order to understand abstract ideas, learners should be engaged with molecular entities as frequently as possible through experience (Picardal & Pano, 2018).

Conceptual Framework

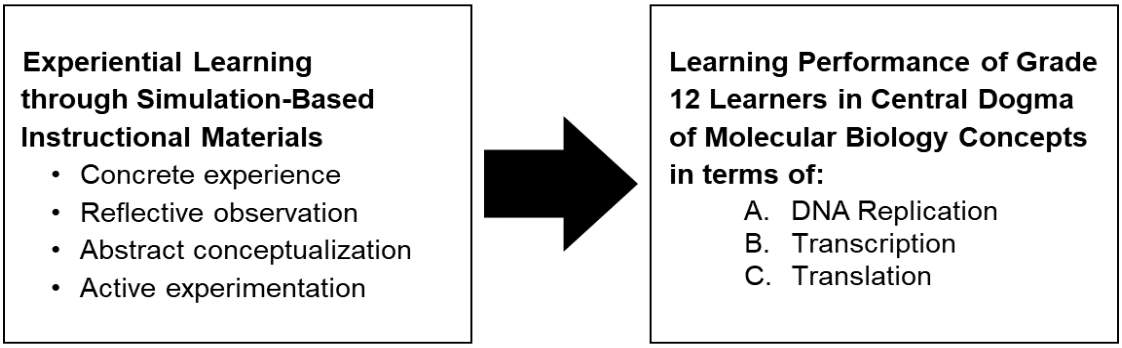
This study was anchored on the learning theories and models of John Dewey's Learning by Doing (Dewey, 1997), and David Kolb's Experiential Learning (Kolb, 1984). These models are interrelated and structured on concrete experiences through hands-on learning. Hence, this study validated the effects of experiential learning, a broad umbrella term used to cover the wide variety of learning by doing approaches, through simulation-based instructional materials on the learning performance of the Grade 12 learners in Central Dogma of Molecular Biology.

Kolb's experiential learning theory (Kolb, 1984) argues that learning works in four stages – *concrete learning* where a learner gets a new experience, *reflective observation* where the learner reflects on their personal experience, *abstract conceptualization* happens as the learner forms new ideas based on the experience and their reflection about it, and *active experimentation* where the learners applies new ideas to the world around them and to assess if there are any modifications to be made. Kolb (1984) posits that learners have their own preferences on how they will enter the cycle of experiential learning, and these preferences boil down to a learning cycle. As a result, learners practice critical thinking, and eventually, can achieve a higher level of understanding of the concepts.

As shown in Figure 1, the elements of experiential learning through simulation-based instructional materials make up the study's conceptual framework.

Figure 1

Conceptual Framework of the Study



Methodology

Research Design

This study utilized a mixed-method approach. The quantitative phase of the study used the pretest and posttest design to determine the learner's mastery level before and after applying the simulation-based instructional materials. For the qualitative phase of the study, semi-structured interviews were conducted in order to reveal the learners' attitude towards the simulation-based instructional materials. This is to examine and strengthen the quantitative data gathered on the effects and significant differences on the sample groups' pretest and post-test scores. One sample pretest-posttest design (Knapp, 2016) was specifically employed in this study. The feature of this research design is that the study is conducted in one (1) sample group only, and the measurements of the samples were taken both before and after the method was applied (Fraenkel & Wallen, 2000).

Research Participants

The participants of this study were the learners from one (1) section of the Grade 12 STEM strand of Notre Dame of Marbel University-Integrated Basic Education Department Senior High School. To ensure the containment of the data, and to avoid contamination and inconsistencies in the results of the study, the following inclusion criteria in selecting the participants were employed: (1) the participants must be enrolled in the Grade 12 STEM strand in the second semester of the school year 2020-2021, (2) any gender with no age restrictions were recognized as participants, and (3) the participants must be currently taking General Biology 2 subject.

Sampling Technique

The participants of this study were mainly selected based on the purposive sampling technique. It was a non-probability sampling technique in which the researchers carefully selected the sample with the assumption that each participant would be able to provide specific and rich data that are important to achieve the purpose of the study. Students from one (1) section of Grade 12 STEM were chosen as the study participants.

Research Instrument

For the gathering of quantitative data, the study used a Pretest-Posttest Questionnaire adapted from the study of Newman et al (2016). It was used to assess the mastery level of the learners on the concepts Central Dogma of Molecular Biology. The questionnaire consisted of forty (40) multiple-choice items covering the following sub-topics: a) DNA Replication, b) Transcription, and c) Translation. The reliability of the questionnaire was assessed by using the split-half method. Right answers were given 1 point and wrong answers were given with 0. The data analysis revealed that the pretest-posttest questionnaire had a Guttman Split Half coefficient of 0.992. This indicated that the questionnaire scale had a high level of internal consistency (DeVillis, 2003; Kline, 2005). The mastery level scores in the pretest and posttest of the learners on the concepts of Central Dogma of Molecular Biology were described using the scale in Table 1.

Table 1

Descriptive Rating of Learner's Mastery Level Scores on the Central Dogma of Molecular Biology Concepts

No. of Items			Percentile	Description	Interpretation
8	16	40			
6.41-8.00	12.81-16.00	33-40	81-100	Advanced	Very High
4.81-6.40	9.61-12.80	25-32	61-80	Proficient	High
3.21-4.80	6.41-9.60	17-24	41-60	Approaching Proficiency	Average
1.61-3.20	3.21-6.40	9-16	21-40	Developing	Low
0.00-1.60	0.00-3.20	0-8	0-20	Beginning	Very Low

Note. Adapted from "Conceptual Understanding, Attitude and Performance in Mathematics of Grade 7 Students* by Andamon, J. and Tan, D. (2018), *International Journal of Scientific & Technology Research, 7*(8), 96-105. https://www.researchgate.net/publication/327135996

For the gathering of qualitative data, the researchers used semi-structured interview guide questions adopted from the study of Ulukok, and Sari (2016) to reveal the attitudes of the participants exposed to the simulation-based instructional materials. The tool contained five (5) open-ended questions that revolved around the utilization of the instructional materials.

Development and Validation of Session Plans

The Department of Education curriculum guide was considered in preparing the content to be included in the session plans. The topic considered in the study was the Central Dogma of Molecular Biology. This topic was chosen and included in the study as it was cited to be a difficult topic to teach and learn by the teachers and learners, respectively (Knippels et al., 2005; Kozma et al., 2000; Lewis et al., 2000; Reddy & Mint, 2017). Furthermore, teachers of the subject suggested this topic because of more complicated mechanisms involved. The experience of the researchers also provided information that this was the topic found most difficult and with least mastered competencies. This topic involves DNA and RNA structures that were tedious to analyze and draw on the chalkboard and could be provided with a computer-simulation material.

After identifying and selecting the topic, session plans were developed and validated. Four (4) expert validators were asked to evaluate the developed session plans. The evaluation tool adapted from the study of Mercado (2020) was used. The tool contains three main criteria: (1) content quality; (2) technical quality; and (3) instructional quality. All of the criteria contained nine (9) indicators. A 5-point Likert scale shown in Table
2 was used to describe and interpret the validation results of the developed session plans. The means were calculated to evaluate the developed materials in terms of their content, technical, and instructional qualities.

Table 2

Rating Scale for the Developed Session Plans Validation

Rating Scale	Range	Description
1	1.00 – 1.50	Not Applicable
2	1.51 – 2.50	Strongly Disagree
3	2.51 – 3.50	Disagree
4	3.51 – 4.50	Agree
5	4.51 – 5.00	Strongly Agree

Note. Adapted from "Development of Laboratory Manual in Physics for Engineers," by Mercado, J. (2020), *International Journal of Science and Research.* https://www.ijsr.net/search_index_results_paperid.php?id=SR201002120011

The validation result showed that the validators strongly agreed on the content, technical, and instructional qualities of the developed session plans on Central Dogma of Molecular Biology.

Simulation-Based Instructional Materials Used in the Study

The simulation-based instructional materials used in the study were properly incorporated in the developed session plans. The LabXchange® Simulation Package on DNA Replication and Central Dogma developed by the Harvard Faculty of Arts and Sciences and funded through the Amgen

Foundation, Gene Expression Simulation developed by Colorado University's Physics Education Technology (PhET®) Project, DNA Interactive Simulation developed by Cold Spring Harbor Laboratory, and Holt's Central Dogma Simulations developed by Holt (2008), were integrated with the session plans to deliver the intended outcomes in teaching the Central Dogma of Molecular Biology. All the interactive simulation tools were adapted into English.

Data Gathering

Before the conduct of the study, the following were prepared and ensured: (a) development and establishment of the reliability of the Pretest- Posttest Questionnaire, (b) identification of appropriate simulation-based instructional materials anchored to the topic and curriculum, (c) review of resource materials and instruments to ensure the coherence of the competencies with the Department of Education (DepEd) – Curriculum Guide, and (d) development and validation of the session plans. The researchers initially wrote a permission letter explaining the purpose and nature of the study to the School Principal of Notre Dame of Marbel University-Integrated Basic Education Department Senior High School. Subsequently, a letter of invitation and the approved informed consent form were sent online to the participants and their parents to seek their approval. The goal and their participation in the research were also explained to them.

The identified participants were asked to answer the pretest using the Pretest-Posttest Questionnaire. The pretest was administered through Schoology® - the official learning management system of the school. The participants answered the test synchronously for one (1) hour. The test was given to gauge the mastery level of the learners in Central Dogma of Molecular Biology before applying the simulation-based instructional materials. The sample group went through ten (10) online teaching sessions based on the developed session plans. The official learning management system of the school - Schoology®, was used as the platform. The simulation-based instructional materials from LabXchange®, PhET®, DNA Interactive®, and Holt's® Simulations were used during the online teaching sessions. The researchers delivered the instructions, methods, and instructional materials to prevent external factors and bias. The delivery of instructions using the simulation-based instructional materials ran for one week. Two (2) hours of online teaching were administered per day, and one session was administered per hour. The same set of questions in the pretest-posttest questionnaire was administered for the posttest. The researchers administered the tests online.

The semi-structured interview was administered to the nine (9) identified participants from the sample group. The participants were requested to answer five (5) semi-structured interview questions online. This was to examine and strengthen the quantitative data gathered on the effects and significant differences on the participants' pretest and post-test scores. The date and time of the interview were scheduled based on the participants' convenience. The participants were coded as S1 to S9 to keep their identities confidential.

Data Analysis

The mean and percentage were used to determine the mastery level scores of the participants before and after the conduct of the study on the concepts of Central Dogma of Molecular Biology. The paired-samples t-test was used to determine the significant difference in the pretest and posttest scores on the mastery level of the participants on the concepts of Central Dogma of Molecular Biology. Meanwhile, the data gathered from the semi-structured interview were subjected to Thematic Content Analysis to reveal the learners' attitudes when exposed to simulation-based instructional materials. Verbatim data from the interviews were transcribed. Subsequently, the transcripts were analyzed to classify relevant sentences for further coding, involving sentences, terms, or long statements (Factor et al., 2017). The reliability of the qualitative data was ensured by sending back the initial codes together with the significant statements to the participants for checking.

This is to ensure that the codes generated include the real experiences of the participants (Birt et al., 2016). Related codes were clustered into categories (Saldana, 2009). Consequently, categories were synthesized in an overarching theme that later became instrumental in revealing the learners' attitude when exposed to the simulation-based instructional materials.

Ethical Considerations

This study complied with the ethical standards set by the Notre Dame of Marbel University. Furthermore, the study was conducted with the informed consent of all the participants. No sensitive information was drawn from the participants. The researchers strictly followed interview protocols before conducting the semi-structured interview and ensured that the participants and their parents approved the electronic informed consent form. The participants were assured that their participation would be private, confidential, and voluntary. The participant's identity would also remain anonymous. It was also emphasized to the participants that the gathered data from the semi-structured interview will be used purely for academic purposes only and shall be treated with the utmost confidentiality.

Results and Discussions

Pretest and Posttest Scores of the Learners

This study sought to determine the mean mastery level scores of the learners in Central Dogma of Molecular Biology concepts before and after the conduct of the study. The mean and percentage of the pretest scores of the learners on the Central Dogma of Molecular Biology concepts were computed. Based on the percentage values, descriptions were offered. The learners' pretest mean mastery level scores on the concepts of Central Dogma of Molecular Biology are presented in Table 3.

Table 3

Learners' Pretest Mean Mastery Level Scores on the Central Dogma of Molecular Biology Concepts

Concepts	No. of Items	Mean ± SD	Percentage	Description
A. DNA Replication	16	10.17 ± 2.46	63.54	Proficient
B. Transcription	8	3.81 ± 1.00	47.66	Approaching Proficiency
C. Translation	16	9.04 ± 3.15	56.51	Approaching Proficiency
Overall	**40**	**23.02 ± 5.82**	**57.55**	**Approaching Proficiency**

Note. 0%-20% = Beginning 61%-80% = Proficient
21%-40% = Developing 81%-100% = Advanced
41%-60% = Approaching Proficiency

The pretest result showed that, out of 16 items on the concept of DNA Replication, the learners obtained a mean mastery level score of 10.17 ± 2.46 or 63.54%. This implied that the learners were "proficient" in the concept of DNA Replication. On the other hand, out of 8 items on the concept of Transcription, the learners obtained a mean mastery level score of 3.81 ± 1.00 or 47.66%. This suggested that the learners were "approaching proficiency" on the concept of Transcription. Likewise, out of 16 items on the concept of Translation, the learners obtained a mean mastery level score of 9.04 ± 3.15 or 56.51%. This indicated that the learners were "approaching proficiency" on the concept of Translation.

Nevertheless, out of the total 40 items on Central Dogma of Molecular Biology concepts, the learners registered an overall mean mastery level score of 23.02 ± 5.82 or 57.55%. This revealed that the learners were generally "approaching proficiency" on the concepts of Central Dogma of Molecular Biology before conducting the study.

On the other hand, the mean and percentage of the posttest scores of the learners on the Central Dogma of Molecular Biology concepts were computed. Based on the percentage values, descriptions were offered. The posttest mean mastery level scores of the learners on the concepts of Central Dogma of Molecular Biology were presented in Table 4.

Table 4

Learners' Posttest Mean Mastery Level Scores on the Central Dogma of Molecular Biology Concepts

Concepts	No. of Items	Mean ± SD	Percentage	Description
A. DNA Replication	16	14.02 ± 1.44	87.63	Advanced
B. Transcription	8	6.35 ± 0.98	79.43	Proficient
C. Translation	16	13.06 ± 1.33	81.64	Advanced
Overall	**40**	**33.44 ± 2.94**	**83.59**	**Advanced**

Note. 0%-20% = Beginning 61%-80% = Proficient
21%-40% = Developing 81%-100% = Advanced
41%-60% = Approaching Proficiency

The posttest result showed that, out of 16 items on the concept of DNA Replication, the learners obtained a mean mastery level score of 14.02 ± 1.44 or 87.63%. This suggested that the learners were "advanced" in the concept of DNA Replication. On the other hand, out of 8 items on the concept of Transcription, the learners obtained a mean mastery level score of 6.35 ± 0.98 or 79.43%. This indicated that the learners were "proficient" in the concept of Transcription. Nevertheless, out of 16 items on the concept of Translation, the learners obtained a mean mastery level score of 13.06 ± 1.33 or 81.64%. This indicated that the learners were "advanced" on the concept of Translation. Meanwhile, it could also be deduced in Table 4 that, out of the total 40 items on the concepts of Central Dogma of Molecular Biology, the learners registered an overall mean mastery level score of 33.44 ± 2.94 or 83.59%. This revealed that the learners were "advanced" on the concepts of Central Dogma of Molecular Biology after conducting the study.

To determine if there was a difference between the mean mastery level scores of the learners on the Central Dogma of Molecular Biology concepts before the conduct of the study and the learners' mean mastery level scores after the simulation-based instructional materials were employed, a paired-samples t-test was utilized. Exploratory data analysis revealed that were no outliers in the distribution. The pretest and posttest scores distributions were normally distributed as assessed by the Shapiro- Wilk's test with p=0.313 and p=0.260, respectively. Table 5 demonstrated the paired-samples t-test of the pretest and posttest mean mastery level scores of the learners on the Central Dogma of Molecular Biology concepts.

Table 5

Paired-Samples T-Test of the Learners' Pretest and Posttest Mean Mastery Level Scores on the Central Dogma of Molecular Biology Concepts

Concepts	Pretest Mean ± SD	Posttest Mean ± SD	Mean Difference
A. DNA Replication	10.17 ± 2.46	14.02 ± 1.44	3.85*
B. Transcription	3.81 ± 1.00	6.35 ± 0.98	2.54*
C. Translation	9.04 ± 3.15	13.06 ± 1.33	4.02*
Overall	**23.02 ± 5.82**	**33.44 ± 2.94**	**10.42***

Note. *significant at 0.05 level of significance

The result of the paired-samples t-test revealed a statistically significant difference ($p<0.05$) between the pretest and posttest mean mastery level scores of the learners on the concepts of DNA Replication, Transcription, and Translation. Likewise, a statistically significant increase in the mastery level scores of 3.85, 2.54, and 4.02 on DNA Replication, Transcription, and Translation concepts was observed, respectively.

Furthermore, it could be observed in Table 5 that there was a statistically significant difference ($p<0.05$) between the overall pretest (23.02 ± 5.82) and posttest (33.43 ± 2.94) mean mastery level scores of the learners. Accordingly, a statistically significant increase in the overall mastery level scores of 10.42 on the concepts of Central Dogma of Molecular Biology was observed.

The low pretest mean mastery level score of the learners on the concepts of Central Dogma of Molecular Biology connotes less prior knowledge and misconceptions of the concepts as they need the prerequisite knowledge on cell division and reproduction to be able to explain the process of gene transmission correctly. This finding supported the argument of Change and Anderson (2020) and Picardal and Pano (2018) that there was a lack of basic knowledge on Genetics and Genetics technologies by the learners, and widespread misconceptions at various levels. Meanwhile, the significant increase in the posttest mean mastery level score of the learners signified the pronounced effect of the simulation-based instructional materials to the learners' learning on the concepts of Central Dogma of Molecular Biology. This indicated that learners had developed a conceptual understanding of DNA Replication, Transcription, and Translation mechanisms. Computer simulations were proven to develop learners' thinking and interpretation skills, thus, resulting in the development of higher-order thinking skills (Efe & Efe, 2011). The present study conformed to the different research findings that the use of computer simulations in teaching resulted in better learning outcomes for the learners (DeCaporale-Ryan et al., 2016; Gunda & Dongeni, 2017; Mceneaney, 2016; Olga, et al., 2020).

One of the reasons for the success of the learners in the posttest result was probably the fact that simulations help learners to visualize processes that seem abstract and complex such as the structure and composition of DNA, DNA replication, the use of knowledge in DNA to generate messenger RNA (mRNA), and the processing of functional proteins using the mRNA as a template.

According to Gunda and Dongeni (2017), utilizing visual instructional tools in teaching and learning environments is relevant and highly useful since it allows learners to envision and explore the implications of the model's rules for a method or system. This, in turn, can aid in the development of the learner's self-confidence and logical thinking skills (Mceneaney, 2016). There are some benefits of using models to teach the Central Dogma of Molecular Biology. They are both secure and practical to use. Furthermore, they often take less time to manipulate and can be replayed as many times as possible (Sahin, 2006). Decades of studies have also identified a correlation between constructive motivation and a good learning atmosphere using computer simulations (DeCaporale-Ryan et al., 2016; Flanagan, 2009; Gunda & Dongeni, 2017; Mceneaney, 2016; Olga et al., 2020; Reddy & Mint, 2017; Ulokok & Sari, 2016).

On the contrary, several studies have demonstrated that using computers and technology-based instructional materials in the teaching- learning process elicits some negative reactions. Greene (2001) mentioned that digital technology has the potential to reduce the interpersonal component of teaching since that the essence of teaching is the development of knowledge through relationships with learners in order to help them understand the concepts. The intertwining of emotional and intellectual bonds gives meaning to the teaching-learning process. Similarly, Bautista (2011) asserts that computers and the internet cannot imitate the art of teaching. These resources may enhance an already high- quality educational experience, but relying on them as the sole source of learning is a costly mistake.

Learners' Attitudes on Simulation-Based Instructional Materials

The participants' responses through semi-structured interviews were analyzed and synthesized into specific codes. Similar codes were grouped into categories and were consequently synthesized in an overarching theme. Based on the responses of the participants, one theme emerged. This theme collectively characterized learners' attitude exposed to simulation-based instructional materials: *Engaged in Experiential Learning* (Table 6).

Table 6

Learners' Attitudes on Simulation-Based Instructional Materials

Codes	Categories	Theme
Interactive Engaged in deeper understanding of lesson through experience Engaged in better understanding of concepts through interaction Engaged in better understanding and application of concepts through interaction	Engaged in Better Concept Attainment through Experience	Engaged in Experiential Learning
Helpful in understanding of concepts through visuals Engaged in better understanding of concepts through visuals Engaged in easy understanding of concepts through visuals	Engaged in Better Concept Attainment through Visuals	

Codes	Categories	Theme
Engaged in self –reflecting questions Engaged in evaluating one's action	Engaged in evaluative thinking	Engaged in Experiential Learning

Engaged in Experiential Learning

The result of the thematic content analysis on the responses of the learners revealed that they were engaged in experiential learning with the use of simulation-based instructional materials. Most of them pointed out that using the computer simulations made them more engaged with the better attainment of concepts through experience. They also emphasized that they better understood the concepts because they could experience the activity first-hand through engaging interactions. The following were some of the responses of the participants:

S5 shared:

"… mas lalalong maintindihan yung lesson. Tapos hindi lang yung parang nag iimagine ka lang pero parang na eexperience mo talaga. Although simulation lang siya parang na eexperience mo pa rin kung paano ba talaga naga work yung bagay bagay." [… the lesson was better understood. You do not just imagine, but it seems like you can really experience. Although it is just a simulation, it seems like you can still experience how things work.]

S4 also added:

"…you can interact, and you are the one who is manipulating, and there is a clear picture and view on how the processes are made. You can see it not just read it, and the process is very instructional sir. The way you interact with the simulations it can help you better understand the lesson."

From the gathered data, it can also be noted that learners were able to understand the concepts better using the simulation-based instructional materials because they could visualize the information, giving them a concrete experience of what is happening in the processes. Some of the responses of the participants were the following:

S6 emphasized:

"… kung i-compare ko siya sa usual na lessons, more on presentations lang na usual, hindi ko kaayo ma grasp ang mga ideas and hindi ko ma follow ang instructions properly. Whereas kung may simulation, makita ko siya properly at mas maintindihan kung ano ang nangyayari sa process mismo." […if I were to compare it to the usual lessons, more on the usual presentation, I cannot really grasp the ideas and I cannot follow the instructions properly. Whereas if there is simulation, I can see it properly and I can really better understand what is happening in the process.]

S5 shared:

"… makita po namin kung paano nagawork yung DNA. Hindi lang po imagination namin parang navivisualize rin po namin kung ano po talaga yung nangyayari sa loob. Mas na iintindihan po namin yung processes." [… we can see how the DNA works. We do not just imagine, but we can really visualize what is happening inside. We can really understand better the processes.]

Meanwhile, the learners also pointed out that the simulation-based instructional materials engaged them in evaluative thinking. They emphasized that they were able to evaluate the consequences of their actions with the computer simulations. The following were some of the responses:

S8 shared:

"... it can give me chance to evaluate the consequences of my actions and the importance of minimizing my errors, sir."

S4 also added:

"... we think of the process like we also question ourselves how did it get to this, like... we always asked questions how and why instead of just simply defining."

The results of the study presented collectively revealed that computer simulations engaged learners to understand the concepts through experiential learning better. This strengthened and supported the significant increase in the posttest mean mastery level score of the learners that the simulations based-instructional materials have pronounced effects on the learners' learning on the concepts of Central Dogma of Molecular Biology. According to Juan et al. (2017), experiential learning such as simulation is commonly used in teaching to engage learners in critical and evaluative thinking and self-directed learning (Pugh et al., 2020). It allows learners to apply things they have learned to real world experiences immediately. In the study conducted by Hakeem (2001), learners engaged in experiential learning have a greater understanding of their subject matter than learners in a traditional lecture class. Furthermore, DeCaporale-Ryan et al. (2016) posited that computer simulations could enhance learning by engaging learners to create dynamic systems models by combining words with pictures. This also conforms to the study of Gunda and Dongeni (2017) that computer simulations can engage learners to visualize and investigate the consequences of the rules of the model for a system and develop a conceptual understanding that can reveal learners' thoughts, ideas, and experiences (Isiaka & Mudasiru, 2016).

Similarly, the data collected revealed that learners were actively involved in the learning process through interacting in practical, dynamic, complex, and evaluative contexts. According to Abelsson (2017), active participation in learning entails evaluating what happens before and after an operation. When learners use an evaluative method focused on a hypothesis or personal interactions, they develop their analytical reasoning and more profound comprehension of concepts (Cant & Cooper, 2017). Furthermore, several authors emphasized the effectiveness of using computer simulations in creating scenario-based environments in which learners can interact and apply their knowledge and skills to solve real-world problems, improve their learning and thinking power, and evaluative thinking (Gunda & Dongeni, 2017; Mceneaney, 2016; Olga et al., 2020).

Conclusions and Recommendations

This study sought to determine the mean mastery level scores of the Grade 12 learners in Central Dogma of Molecular Biology concepts before and after the conduct of the study and their attitudes on the simulation-based instructional materials. Results of the study showed that the learners were proficient in the concept of DNA Replication and approaching proficiency in the concepts of Transcription and Translation before the conduct of the study. On the other hand, the learners were advanced in the concepts of DNA Replication and Translation and were proficient in the concept of Transcription after the conduct of the study. Furthermore, there was a significant difference ($p<0.05$) in the mean mastery level scores of the learners on the concepts of Central Dogma of Molecular Biology before and after the conduct of the study. The thematic content analysis revealed that the learners were engaged in experiential learning using simulation-based instructional materials. This strengthened and supported the significant increase in the posttest mean mastery level score of the learners that the simulations based-instructional materials have pronounced effects on the learners' learning on the concepts of Central Dogma of Molecular Biology.

However, this study was conducted on a small sample size of participants; hence, to conduct further study on a broader scope to improve the effectiveness and practicability of the simulation-based instructional materials are suggested. The simulation-based instructional materials used in the study were also limited and primarily based on the researchers' preferences; hence, it is suggested that other computer-aided simulation tools and educational software be used in teaching the Central Dogma of Molecular Biology concepts and that their effectiveness towards learners' learning performance be assessed, as well as any potential problems with their use to validate their usefulness further. While the current study may be limited to only a few participants, this research could serve as a baseline for succeeding simulation-based instructional materials studies in science education.

References

Abelsson, A. (2017). Learning through simulation. *Disaster and Emergency Medicine Journal, 2*(3), 125–128. https://doi.org/10.5603/demj.2017.0027

Adarlo, G., & Jackson, L. (2017). *For whom is K-12 education: a critical look into twenty-first century educational policy and curriculum in the Philippines.* Proceedings of the Educating for the 21st Century, pp. 207–223. Springer Press

Andamon, J. & Tan, D. (2018). Conceptual Understanding, Attitude and Performance in Mathematics of Grade 7 Students. *International Journal of Scientific & Technology Research, 7*(8), 96–105. https://www.ijstr.org/final-print/aug2018/Conceptual-Understanding-Attitude-And-Performance-In-Mathematics-Of-Grade-7-Students.pdf https://www.researchgate.net/publication/327135996_Conceptual_Understanding_Attitude_And_Performance_In_Mathematics_Of_Grade_7_Students

Angelini, M. L. (2016). Integration of the pedagogical models "simulation" and "flipped classroom" in teacher instruction. *SAGE Open, 6*(1), 1–8 https://doi.org/10.1177/2158244016636430

Anoba, J. L. & Cahapay, M. (2020). The Readiness of Teachers on Blended Learning Transition for Post-COVID-19 Period: An Assessment Using Parallel Mixed Method. *PUPIL: International Journal of Teaching, Education and Learning, 4*(2), 295–316. https://doi.org/10.20319/pijtel.2020.42.295316

Arrieta, G., Dancel, J., & Agbisit, M. J. (2020). Teaching Science in The New Normal: Understanding The Experiences of Junior High School Science Teachers. *Jurnal Pendidikan Mipa, 21*(2), 146–162. https://doi.org/10.23960/jpmipa/v21i2.pp146-162

Bautista, D. (2011). Classroom materials and aids. *The Philippine Journal of Education. 8*(2), 1–18. https://doi.org/10.1177/1049732316654870

Becker, L. R.,& Hermosura, B. A. (2019). *Simulation education theory.* Comprehensive Healthcare Simulation: Obstetrics and Gynecology, 11–24. https://doi.org/10.1007/978-3-319-98995-2_2

Birt, L., Scott, S., Cavers, D., Campbell, C., & Walter, F. (2016). Member checking: A tool to enhance trustworthiness or merely a nod to validation? *Qualitative Health Research, 26*(13), 1802–1811. https://doi.org/10.1177/1049732316654870

Cai, Y., Goei, S. L., & Trooster, W. (2016). *Simulation and serious Games for education.* Springer.

Cant, R. P., & Cooper, S. J. (2017). Use of simulation-based learning in undergraduate nurse education: An umbrella systematic review. *Nurse Education Today, 49*, 63–71. https://doi.org/10.1016/j.nedt.2016.11.015

Change, L., & Anderson, E. (2020). *The New Central Dogma of Molecular Biology.* https://www.researchgate.net/publication/340062231

Creswell, J. W., & Plano Clark, V. L. (2011). *Designing and Conducting Mixed Methods Research* (2nd ed.). Sage Publications Ltd.

DeCaporale-Ryan, L., Dadiz, R., & Peyre, S. E. (2016). Simulation-based learning: From theory to practice. *Families, Systems & Health, 34*(2), 159. https://search.proquest.com/scholarly-journals/simulation-based-learning- theory-practice/docview/1799223712/se-2?accountid=33511

Department of Education. (2020). *PISA 2018–National Report of the Philippines.* OECD. Paris, France.

De Vellis, R. F. (2003). *Scale Development: Theory and Applications* (2nd ed.). Sage Publications.

Dewey, J. (1997). *Experience and Education: The Kappa Delta Pi Lecture Series.* https://www.schoolofeducators.com/wp-content/uploads/2011/12/EXPERIENCE-EDUCATION-JOHN-DEWEY.pdf

Dukes, A. (2020). Teaching an instrumental analysis laboratory course without instruments during the COVID-19 pandemic. *Journal of Chemical Education, 97*(9), 2967. https://dx.doi.org/10.1021/acs.jchemed.0c00648

Efe, H. A., & Efe, R. (2011). Evaluating the effect of computer simulations on secondary biology instruction: An application of Bloom's taxonomy. *Scientific Research and Essays, 6*(10), 2137-2146. https://dx.doi.org/10.5897/SRE10.1025

Factor, E. M., Matienzo, E. T., & de Guzman, A. B. (2017). A square peg in a round hole: Theory-practice gap from the lens of Filipino student nurses. *Nurse Education Today*, 57, 82-87. https://doi.org/10.1016/j.nedt.2017.07.004

Flanagan, J. (2009). Patient and Nurse Experiences of Theory-Based Care. *Nursing Science Quarterly,* 22(2), 160–172. https://doi.org/10.1177/0894318409331937

Fraenkel, R. J., & Wallen, E. N. (2000). *How to design and evaluate research in education* (4th ed.). McGraw-Hill.

Greene, B. (2001). *A 21st century ideas for schools: Log off and learn. Chicago Tribune*, Sec 2, p. 1.

Gunda, L., & Dongeni, M. (2017). *Intelligent interactive system for E-learning.* Victoria Falls: European Alliance for Innovation (EAI). https://dx.doi.org/10.4108/eai.20-6-2017.2275849

Gruler, A., De Armas, J., Juan, A. A., & Goldsman, D. (2019). Modelling human network behaviour using simulation and optimization tools: the need for hybridization. *SORT-Statistics and Operations Research Transactions*, 193–222. https://doi.org/10.2436/20.8080.02.85

Hakeem, S. A. (2001). Effect of experiential learning in business statistics. *Journal of Education for Business,* 77, 95–98.

Holt, W. (2008). *Holt Biology*, pp. 273-325. Holt, Rhinehart and Winston Publishing House.

Huang, J. (2020). Successes and challenges: Online teaching and learning of chemistry in higher education in china in the time of COVID-19. *Journal of Chemical Education,97*(9), 2810. http://dx.doi.org/10.1021/acs.jchemed.0c00671

Isiaka, A. G., & Mudasiru, O. Y. (2016). Effects of computer-assisted jigsaw II cooperative learning strategy on physics achievement and retention. *Contemporary Educational Technology,* 7(4), 352–367. https://www.proquest.com/scholarly-journals/effects-computer-assisted-jigsaw- ii-cooperative/docview/2135157270/se-2?accountid=33511

Juan, A. A., Loch, B., Daradoumis, T., & Ventura, S. (2017). Games and simulation in higher education. *International Journal on Educational Technology in Higher Education,* 4(37). https://doi.org/10.1186/s41239-017-0075-9

Kline, R. B. (2005). *Methodology in the social sciences.* Principles and practice of structural equation modeling (2nd ed.). Guilford Press.

Knapp, T. R. (2016). Why is the one-group pretest-posttest design still used? *Clinical Nursing Research,* 25(5), 467–472. https://dx.doi.org/10.1177/1054773816666280

Knippels, M., Waarlo, A. J., & Boersma, K. (2005). Design criteria for learning and teaching genetics. *Journal of Biological Education, 39*(3), 108–113. https://doi.org/10.1080/00219266.2005.9655976

Kolb, D. (1984). *Experiential learning: Experience as the source of learning and development.* Prentice Hall.

Kozma. R., Chin, E., Russell, J., & Marx, N. (2000). The Roles of Representations and Tools in the Chemistry Laboratory and their Implications for Chemistry Learning. *Journal of Learning Science, 9*(2), 105. https://doi.org/10.1207/s15327809jls0902_1

Kutz, J. N., Brunton, S. L., Brunton, B. W., & Proctor, J. L. (2016). Dynamic mode decomposition: data-driven modeling of complex systems. *Society for Industrial and Applied Mathematics,* 1–24. https://doi.org/10.1137/1.9781611974508

Lameras, P., Arnab, S., Dunwell, I., Stewart, C., Clarke, S., & Petridis, P. (2016). Essential features of serious games design in higher education: Linking learning attributes to game mechanics. *British Journal of Educational Technology, 48*(4), 972–994. https://doi.org/10.1111/bjet.12467

Lewis, J. (2000). Genes, Chromosomes, Cell division and Inheritance – Do Students See Any Relationship? *International Journal of Science Education, 22*(2), 177–195. https://doi.org/10.1080/095006900289949

Mahaffey, A. L. (2020). Chemistry in a cup of coffee: Adapting an online lab module for teaching specific heat capacity of beverages to health sciences students during the COVID pandemic. *Biochemistry and Molecular Biology Education, 48*(5), 528–531. https://dx.doi.org/10.1002/bmb.21439

Marbach-Ad, G., Rotbain, Y., & Stavy, R. (2008). Using Computer Animation and Illustration Activities to Improve High School Students' Achievement in Molecular Genetics. *Journal of Research in Science Teaching, 45*(3), 273–292. https://dx.doi.org/10.1002/tea.20222

Marshall, P. A. (2017). A hands-on activity to demonstrate the central dogma of molecular biology via a simulated VDJ recombination activity. *Journal of Microbiology & Biology Education, 18*(2), 1–4. https://doi.org/10.1128/jmbe.v18i2.1277

Masoud, N., & Bohra, O. P. (2020). Challenges and opportunities of distance learning during covid-19 in UAE. *Academy of Accounting and Financial Studies Journal*, 24, 1–12. https://search.proquest.com/scholarly-journals/challenges-opportunities-distance-learning-during/docview/2469848713/se-2?accountid=33511

Mceneaney, J. E. (2016). Simulation-based evaluation of learning sequences for instructional technologies. *Instructional Science, 44*(1), 87–106.https://dx.doi.org/10.1007/s11251-016-9369-x

Mercado, J. (2020). Development of Laboratory Manual in Physics for Engineers. *International Journal of Science and Research, 9*(10), 200–210. https://www.ijsr.net/search_index_results_paperid.php?id=SR201002120011

Newman, D., Catavero, C., & Wright, K. L. (2012). Students Fail to Transfer Knowledge of Chromosome Structure to Topics Pertaining to Cell Division. *CBE - Life Sciences Education, 11*(4), 425–436. https://doi.org/10.1187/cbe.12-01-0003

Newman, D. L., Snyder, C. W., Fisk, J. N., & Wright K. L. (2016). Development of the Central Dogma Concept Inventory (CDCI) assessment tool. *CBE-Life Sciences Education, 15*(2), ar9–ar9. https://doi.org/10.1187/cbe.15-06-0124 PMID: 27055775

Olga, C., Heitzmann, N., Matthias, S., Doris, H., Seidel, T., & Fischer, F. (2020). Simulation-based learning in higher education: A meta-analysis. *Review of Educational Research, 90*(4), 499–541. https://dx.doi.org/10.3102/0034654320933544

Picardal, M. & Pano, J. (2018). Facilitating Instruction of Central Dogma of Molecular Biology through Contextualization. *Journal of Teacher Education and Research, 13*(2), 118-132. https://doi.org/10.5958/2454-1664.2018.00012.5

Pugh, K., Kriescher, D., Cropp, S., & Younis, M. (2020). Philosophical groundings for a theory of Transformative experience. *Educational Theory, 70*(5), 539–560. https://dx.doi.org/10.1111/edth.12443

Reddy, M., & Mint, P. (2017). Impact of Simulation Based Education on Biology Student's Academic Achievement in DNA. *Journal of Education and Practice, 8*(15), 72–75. https://www.iiste.org/Journals/index.php/JEP/article/view/37036/38074

Reshmad'sa, L., & Vijaya Kumari, S. N. (2017). Effect of Kolb's experiential learning strategy on enhancing pedagogical skills of pre-service teachers of secondary school level. *I-Manager's Journal on School Educational Technology, 13*(2), 1–6. https://dx.doi.org/10.26634/jsch.13.2.13825

Rivera, J. G. (2017). Articulating the foundations of Philippine K to 12 Curriculum: Learner-centeredness. *AsTEN Journal of Teacher Education, 2*(1), 59–70. https://po.pnuresearchportal.org/ejournal/index.php/asten/article/view/554/269

Rotbain, Y., Marbach-Ad, G., & Stavy, R. (2008). Using a computer animation to teach high school molecular biology. *Journal of Science Education and Technology*, 17, 49–58. https://dx.doi.org/10.1002/tea.20222.

Sahin, S. (2006). Computer Simulations in Science Education: Implication for Distance Education. *Turkish Online Journal on Distance Education, 7*(4), 132-146. https://www.researchgate.net/publication/26442272_Computer_simulations_in_science_education_Implications_for_distance_education.

Saldana, J. (2009). *The coding manual for qualitative researchers.* SAGE. https://au.sagepub.com/en-gb/oce/the-coding-manual-for-qualitativeresearchers/book243616.

Sunasee, R. (2020). Challenges of teaching organic chemistry during COVID-19 pandemic at a primarily undergraduate institution. *Journal of Chemical Education, 97*(9), 3176–3181. https://doi.org/10.1021/acs.jchemed.0c00542.

Ulukok, S., & Sari, U. (2016). The effect of simulation-assisted laboratory applications on pre-service teachers' attitudes towards science teaching. *Universal Journal of Educational Research, 4*(3), 465–474. https://doi.org/10.13189/ujer.2016.04030.

Van Mil, M. H. W., Boerwinkel, D. J., & Waarlo, A. J. (2013). Modelling Molecular Mechanisms: A Framework of Scientific Reasoning to Construct Molecular Level Explanations for Cellular Behaviour. *Journal of Science and Education*, 22, 93–118. https://doi.org/10.1007/s11191-011-9379-7

Wright, K. L., Fisk, N. J., & Newman, D. L. (2014). DNA ->RNA: What Do Students Think the Arrow Means? *CBE – Life Science Education, 13*(12), 338–348. https://doi.org/10.1187/cbe.CBE-13-09-0188.