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High School Students’ Perspectives on Mathematical Modeling in the Engineering Design Process (RTP)

Jialing Wu, Vanderbilt University

Jialing Wu is an incoming first-year PhD student in Engineering Education at the Ohio State University. She earned her M.Ed. in International Education Policy and Management at Vanderbilt University, Peabody College, and also holds a bachelor’s degree in Mechanical Engineering from China. Her research interests encompass international engineering education, pre-college engineering, as well as the application of quantitative methods and advanced technology in Engineering Education Research (EER).

Mr. Nicolas Leger, Florida International University

Nicolas Léger is currently an engineering and computing education Ph.D. student in the School of Universal Computing, Construction, and Engineering Education (SUCCEED) at Florida International University. He earned a B.S. in Chemical and Biomolecular Engineering from the University of Maryland at College Park in May 2021 and began his Ph.D. studies the following fall semester. His research interests center on numerical and computational methods in STEM education and in Engineering Entrepreneurship.

Dr. Stacy S Klein-Gardner, Vanderbilt University

Dr. Stacy Klein-Gardner serves as an Adjunct Professor of Biomedical Engineering at Vanderbilt University. She is the co-PI and co-Director of the NSF-funded Engineering for US All (e4usa) project and Executive Director of e4usa, the non-profit. Dr. Klein-Gardner is a Fellow of ASEE.

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Abstract

Mathematical modeling skills are essential for engineers to solve real-world problems. While there is a growing emphasis on pre-college engineering education, it remains unclear how pre-college students utilize and perceive mathematical modeling within the engineering design process. Engineering for US All (e4usa) is dedicated to crafting engineering courses for high school students with the goal of enhancing their understanding and skills in the field. In an early unit, e4usa introduced a mathematical modeling lesson based on MATLAB to assist students in simulating impurity removal by water filters. This paper explored the impact of MATLAB activities on students' perspectives on modeling, offering insights for improving future engineering education programs.

This study is part of a broader research project about mathematical modeling in e4usa. The research team conducted surveys, classroom observations, and focus group interviews involving students and teachers participating during the 2022-2023 academic year. In this paper, we present our findings from student focus group data from two schools in different states. We aimed to summarize the emerging themes that described the impact of our intervention. Additionally, we coded the data based on the concepts of Cognitive Load Theory (CLT) to understand the learning process.

As a result, we found the benefits of mathematical modeling with MATLAB in helping them make scientifically informed engineering design decisions by allowing the testing of different materials and providing precise simulating results. However, challenges arose regarding the gap between simulation and prototype building. From the perspective of CLT, MATLAB helped reduce intrinsic load by minimizing prior knowledge requirements. Yet it was still crucial for managing multi-layered intrinsic loads and effectively dealing with extraneous loads.

With the global advancement of technology and engineering, strengthening mathematical modeling skills for pre-college students has become increasingly important. This paper will contribute to the growing body of knowledge regarding how 21st-century students perceive mathematical modeling and provide insights for developing engineering courses.

Introduction

Engineering for US All (e4usa), funded by the National Science Foundation, endeavors to make engineering more accessible and understandable for secondary school students and teachers. It provides an inclusive curriculum focused on practical engineering design experiences, aiming to cultivate engineering literacy, problem-solving abilities, and practical skills [1].

A component of the e4usa curriculum is the integration of MATLAB, a user-friendly mathematical modeling tool in engineering education. This integration aims to bolster students' engineering design and computational thinking skills, thereby rendering the engineering field more approachable; this aligns with educators' suggestions to increase the pipeline of future engineers [2], [3]. Our research explored students' perspectives on applying mathematical modeling in engineering design, particularly MATLAB.

Additionally, we extended the research based on Leger et al., who pointed out in the teacher analysis that learning theories could potentially assist in understanding students' experiences in MATLAB activities [4]. We specifically focused on Cognitive Load Theory (CLT) as a lens to examine students' learning experiences in the MATLAB activities. CLT has been applied in STEM education. For example, Berssanette and Francisco [5] found that CLT provided guidelines for instructional design in teaching computer programming. Impelluso [6] applied CLT to the redesign of a computer programming class for mechanical engineers, improved student outcomes, and enhanced instructor evaluations. Shi et al. conducted a virtual reality experiment among construction workers and underscored the potential for more immersive instruction to enhance working memory in CLT [7].

As part of the e4usa initiatives, this study addressed primarily two key questions: 1) How has MATLAB enabled student engagement in subsequent design activities, and to what extent did it enrich their decision-making processes? 2) What challenges did students face while using the MATLAB design tool, and what improvement could be made to better its effectiveness and user experience in an educational setting?

Water Filter and MATLAB Activities

Aligned with the Grand Challenges in the National Academy of Engineering (NAE), Unit 2 in e4usa engages students in addressing global water supply issues, fostering teamwork, and guiding them through the engineering design process. Unit 2 encompasses 13 lessons, including the topics of water treatment and community relations, engineering design process, defining problems and brainstorming, mathematical modeling, building physical prototypes, testing and iterating the models, and presentation of findings and solutions.

Lesson 2.6 in the unit, titled "Researching a Water Filter: Mathematical Modeling", utilizes MATLAB to help students create a water filtration model. Students explore the filtration efficiency of different media by selecting pre-existing filter materials on the model interface. The mathematical results are displayed through graphical representations and text output, thus allowing students to gain insights for their prototype building. The interactive interface of this process is in "Hide code view" mode on MATLAB, which is intuitive and easy to understand, requiring no prior knowledge of mathematics or coding. Moreover, students with varying levels of coding experience or interest could switch to "View code mode" to gain access to the underlying code behind the mathematical model.

Cognitive Load Theory

Cognitive load theory (CLT) is a theoretical framework that explains how the constraints of human cognition impact the learning process. According to CLT, the learning process involves two key components: working memory and long-term memory. Working memory is limited in its capacity to handle new information, while long-term memory offers near-limitless storage for knowledge. In this context, learning is a process through which new information is processed by working memory and then constructed within long-term memory. When this stored information is required, working memory retrieves it from long-term memory [8], [9]. Figure 1 shows the mechanism of learning in CLT [9].

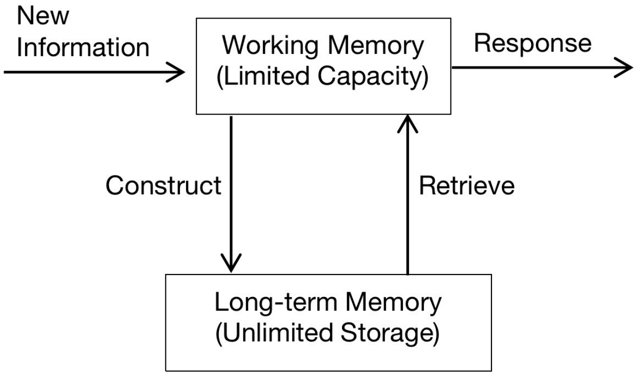


Figure 1. The Mechanism of Learning in CLT: The new information undergoes processing by the working memory and is subsequently integrated into long-term memory. When this information is needed, the working memory retrieves it from long-term memory.

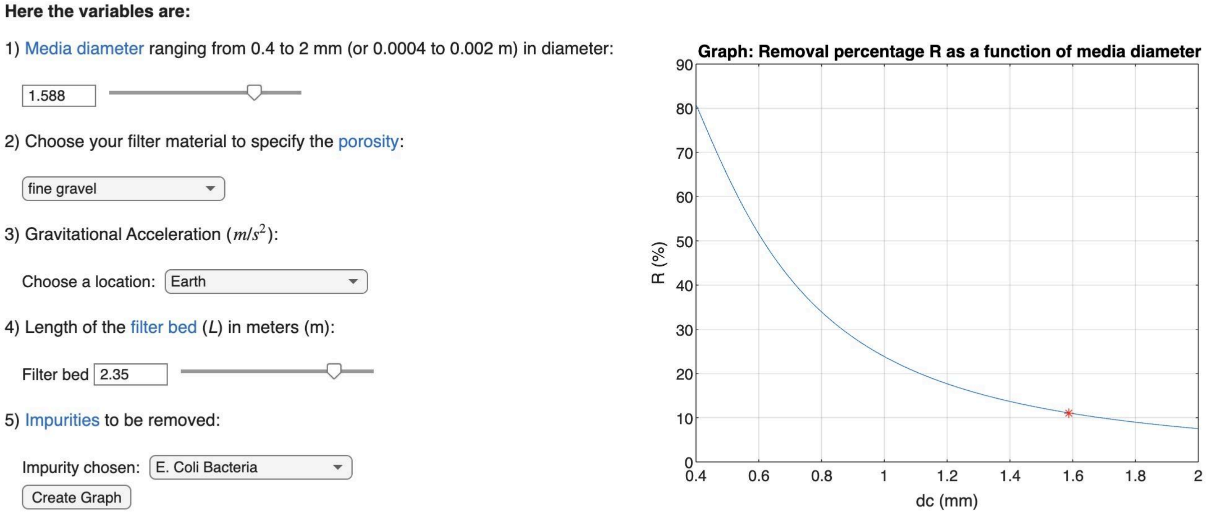
CLT addresses cognitive load through instructional design [8], [9]. Cognitive load represents the demands that an activity imposes on working memory. As mentioned earlier, the capacity of working memory is limited, and an excessive cognitive load can impair its functionality. The new CLT categorizes cognitive load into intrinsic and extraneous loads. Specifically, intrinsic load refers to the complexity of the information being processed and the knowledge to process that information. In other words, it is related to the nature of the information and learners' expertise. Therefore, addressing intrinsic load involves changing the content or enhancing learners' skills. Extraneous load is related to how information is delivered to learners. It could be reduced by effective instructional approaches that lower the complexity of interactions between elements. Appendix A reports 17 instructional effects due to variations in extraneous load [8].

Methods

Context

The MATLAB model allows students to explore the filtration efficiency of different filter materials, aiding them in subsequent model construction. The MATLAB interactive interface defaults to a hidden code view, allowing students to select filter materials, adjust particle spacing, gravitational acceleration, and filter layer thickness, while observing the filtering effects on specific impurities. Figure 2 illustrates the interface of the MATLAB activities for designing water filters.

For example, students could select fine gravel as the filter material, with a diameter of 1.58 millimeters. The water filter is designed with a filter bed length of 2.35 meters and is placed on the earth; students also have the option to place the filter on the moon. If one would like to observe the removal efficiency concerning e. coli bacteria, by clicking the button “Create Graph”, MATLAB will produce a graph on the right. In this case, it reveals a removal rate of e. coli bacteria is 10%. Based on this outcome, it is advisable for students to conduct additional trials in order to achieve a higher removal rate.



Here the variables are:

1) Media diameter ranging from 0.4 to 2 mm (or 0.0004 to 0.002 m) in diameter:

1.588

2) Choose your filter material to specify the porosity:

fine gravel

3) Gravitational Acceleration (m/s^2):

Choose a location: Earth

4) Length of the filter bed (L) in meters (m):

Filter bed 2.35

5) Impurities to be removed:

Impurity chosen: E. Coli Bacteria

Figure 2. The MATLAB Interface for Water Filter Activities: Students interact with the parameters on the left interface, and the results are directly outputted in the graph and text output on the right

In previous semesters, the water filter unit did not include a mathematical modeling lesson. Students proceeded directly to building prototypes after brainstorming and sketching. Teachers reported that students spent a significant amount of time constructing physical water filter prototypes, utilizing a wide range of materials, which posed challenges on resource allocation. Moreover, it was hard for students to gain a comprehensive understanding of the intricate filtrating process, which involves various parameters that affect their further design.

Consequently, we designed the MATLAB activities and hypothesized that by initiating with a mathematical model rather than immediately engaging with physical materials, students could develop a comprehension of the filtration parameters. This theoretical foundation would subsequently inform their prototype building and iterating phase, potentially leading to more informed and effective design choices.

Participants

We presented our findings from student focus group data from two schools: School A, three students, and School B, six students, in two different states. For anonymity reasons, we have not included state information. Table 1 displays the characteristics of the schools. This study has received approval from the Institutional Review Board (IRB).

Table 1. Characteristics of the Schools

School Name	Type of School	Student-Teacher Ratio	Total Students	Title I Eligible	Female Students %	Minority Enrollment %	Black (%)	Asian (%)	Hispanic (%)	White (%)
School A	Public	14	279	YES	49	96	77	0	17	4
School B	Public	20	1756	NO	51	20	2	10	3	80

Analysis

We conducted semi-structured student focus groups at the end of the semester after implementing the MATLAB activity. The focus group questions focused on the topics below:

1. Usage of MATLAB in Designing Water Filter
2. Positive Aspects of MATLAB
3. Challenges with MATLAB
4. Suggestions for Improvement
5. Understanding of Model Definitions
6. Curiosity about Underlying Code
7. Desire for Additional MATLAB Tools
8. Previous Experience with Programming

The focus groups were both held in person, and the sessions were audio-recorded with the consent of the participants and assent of their parents/guardians. The audio recordings were then uploaded to Microsoft Word Online for transcription, with manual corrections made as necessary. The subsequent steps involved inductive coding of the transcripts. Initially, the first author coded the transcript, referencing the codebook from Leger et al[4]. The first round codes include:

- Students make design decisions based on MATLAB
- Students see the value of the MATLAB tool
- Students did not see connection between computational and physical models
- Challenge/Suggestion/Improvement, Exploring MATLAB in depth.

It was followed by comparing these codes with the cognitive load categories in CLT. The codes include: CLT- Intrinsic Load and CLT- Extraneous loads. As intrinsic load is usually irreducible in a learning setting, we further investigated four effects in extraneous load in our third round coding: the split-attention effect, the Self-explanation effect, the variability effect and the modality effect. Once the independent coding phase was completed, the team convened to review and reconcile the codebooks. Appendix B displays the codebook used in the research.

Results

RQ 1: How has MATLAB enabled student engagement in subsequent design activities, and to what extent did it enrich their decision-making process?

The first research question focused on the benefits of the MATLAB tool in enhancing students' design activities. Some students indicated that the MATLAB model was directly related to their design outcomes, helping them measure different materials and providing results. Others recognized some of the benefits of MATLAB, which included clear and informative graph displays, as well as easy access to the platform. From the perspective of CLT, MATLAB helped reduce both the intrinsic load on students' learning by reducing the prior knowledge needed and the extraneous load by reducing the split-attention effect and increasing the self-explanation effect on students' learning.

First, students appreciated the tool for its ability to measure various materials accurately and provide precise data, saving them time on extensive material testing. For example, students shared, "... being able to prioritize or know exactly what each medium impacts was super nice, especially if we knew what priorities we had in terms of the design itself." or "..., and the MATLAB tool helped me test out different materials in which we'd put in the filter, to see how much of the water it would filtrate…, see which material was most efficient." Other students described the parameters and measurement in detail, "I also liked how the measurements were precise, and it gives you a precise result of what would happen when these materials and hole sizes were applied to the overall percentage of filtered water." or " … especially with the E coli concentration levels, because that was a really important criteria that we had for our experiment." The students' application could be explained as the MATLAB tool reduced the intrinsic load in their learning. By presenting the filtering effects through a mathematical modeling tool, students were not required to grasp the chemical and physical principles of various materials' filtration efficiency, thus reducing the demand for prior knowledge and processing.

The reduced intrinsic load also promoted engagement in design activities for the students. It could be proved by their expression about a feeling of real-world modeling: "I think it was just really helpful in regards to how rigorous [it is]. [I] actually felt it was filtrating water and [I see] how efficient it was and how much water would be filtered in percentage rates." Moreover, students thought that the estimates from the model helped in their prototype design. One student said, "..., so we focused on one material [at a time] and made adjustments to its diameter. And then from our results, we decided whether or not we would use it for our experiment." Other students shared a similar view, "The MATLAB tool allowed me to help design my filter because it gave me specific measurements that the filter needed." or "...we got to compare, like the percentages that were removed. And we found that really helpful because it's not the same for every single medium. So we were able to pick and choose what we actually want to incorporate in our actual prototype…"

Other students appreciated the graphing function of the platform: "I also liked how the program gave us a nice little graph that showed us whether it filtered badly, so we wouldn't have to keep on adjusting..." and "... because the picture had a nice size. So I was able to see the measurements clearly along with the fine." Regarding CLT, the presentation of images reduced the split-attention effect in extraneous load. By integrating multiple sources of information about parameters on the screen, the centralized output of images assisted them in obtaining simulation results more intuitively.

Another student valued the easy access to the MATLAB platform, "One small thing but I think a pretty big one is the fact that being in MATLAB, it was a website so it was easily accessible to students...I've done research in the past with other engineering courses. A lot of times, it might be a program and you're crowding around one computer trying to access that..." Expressing gratitude for interactions with the software seemed to align with the self-explanation effect of extraneous load. Instead of only presenting completed examples, interactions in mathematical modeling with enriched prompts encouraged students to self-explain the provided information and facilitate their learning.

RQ 2: What challenges did students face while using the MATLAB design tool, and what improvement could be made to better its effectiveness and user experience in an educational setting?

The second research question addressed the challenges students encountered and potential improvements for the MATLAB tool. In general, students believed there was still a gap between the simulation and the actual building of prototypes. They expressed a need for more comprehensive testing to enhance real-world modeling relevance. They also hoped that the models could have a visual representation and explain the mathematical logic behind the code. These challenges indicated the need to address multi-layered intrinsic loads in mathematical model design and deal with the variability effect, split-attention effect, and modality effect within the extraneous load.

Students highlighted the challenges of measuring real-world materials and aligning the physical prototype with the simulation. One student mentioned "It's really hard to figure out the media diameters of the different ones…depending upon which one you use. If you use just random gravel you find on the road or specifically manufactured gravels for maybe aquariums or something like that. That was definitely difficult, especially with those smaller ones where it was really hard to measure." Another student pointed out, "I think one thing that I faced while making the physical prototype was specifically with the depth of each material. Because our water bottle was irregular in shape, and had a funnel-type structure at the bottom, figuring out the depth of each layer was a little difficult. So maybe if we were given the option to change [the mode] to like the weight of the material that we could put into the water bottle, it would help us with more precision." The students' frustration pointed to the variability effect within the extraneous load. When students transferred from the model to the actual prototype, they were required to adapt the general knowledge from the model to fit real-world conditions. However, given that the variability could increase the intrinsic load, it only enhances the transfer of learning when the overall cognitive load is low. Students, in this case, seemed to encounter an excessive overall cognitive load and thus prevented the transition of knowledge.

Students also expressed a need for the tool to allow for comprehensive testing to enhance real-world modeling. On the MATLAB platform, students could only simulate one material at a time, and some of them reported that "... And my challenge was seeing which materials…would go best together to make the filter better." This limitation reduced the effectiveness of their design process, proved by students' statement, "I also think that our inability to make combinations kind of slows down the process". This dissatisfaction aligned with the findings of RQ1. The inability to integrate information from different sources increased the extraneous load due to the split-attention effect.

Students requested visual representations to mimic actual water filter operations or results. For example, one student commented, "So I want to create a filter to see an actual running simulation of how that filter would work." Another student echoed that, "I want a visual representation of the filter actually stopping those things" One student mentioned, "Potentially, maybe I was thinking maybe the opacity of liquid coming out. Because that's something that wasn't touched upon too much. But it's a very important factor when you're actually testing and then concluding with the filter showing your results. What color is the water coming out? And it just kind of talks about the particles. It doesn't talk specifically about it. your waters are pretty dark. And so that could be, I feel, like a helpful thing that it could potentially include." The students' demands could be explained by the modality effect in extraneous load. Although the Matlab mathematically modeled filtration effects, it primarily used text and images, where it could be helpful to "replace a written explanatory text and another source of visual information (unimodal) with spoken explanatory text and the visual source of information (multimodal)" [5].

In addition, there was a demand for more detailed explanations of the code and mathematics behind the MATLAB models to facilitate better understanding. For example, one student mentioned, "... So I kind of wish there was a little bit of that introduction… If I [know] how to look into that and how exactly they're doing all of that, I think that would have been really interesting just personally", and another student said, "... if there was a way to better explain, like what each part does, and more detail, to help show the math behind it, because at the end of the day, it's coding, but it's also a lot of math involved with creating those different models." The students' demands reflected a desire to increase the intrinsic load in "non-code" modes actively while reducing the intrinsic load in "code" modes. The MATLAB activities aimed to reduce students' intrinsic load by designing student activities primarily based on hidden code modes, emphasizing interaction rather than mathematical research. Therefore, there was only a limited explanation for the code interface. For students, the intrinsic and extraneous loads were different during the learning process. If the total cognitive load in the hidden mode was low, students were more inclined to seek an increase in intrinsic load in non-code modes. There were requirements posed for the design of multi-layered cognitive loads.

Discussion and Limitation

The emergent themes underscore the advantages of utilizing mathematical modeling tools to augment students' comprehension of design concepts and promote their engagement in activities. Previous research echoes similar findings, indicating that students perceive modeling as engaging and instrumental in enhancing their understanding of tasks [10]. Additionally, modeling activities provide students with the freedom to explore various problem-solving approaches, thereby nurturing motivation among them [11].However, enhancing the connection between modeling and solving real-world problems remains a significant challenge. Although students engage with authentic elements within the modeling process [12], their strategies for addressing real-world problems tend to be either mathematical or contextual, but seldom integrate both, due to the high level of knowledge required [13]. This indicates that model designers and educators need to establish stronger connections between modeling and real-world problems in both curriculum design and practical teaching.

Our findings also indicate that the modeling tool served as scaffolding in accordance with CLT, assisting high school students in their learning process. The modeling tool appeared to alleviate cognitive load by reducing prior knowledge and effectively integrating information. This echoes Tang and Holton [14] implemented MATLAB in an undergraduate dynamics course, where they observed potential for enhancing student learning by optimizing working memory. Educators could consider utilizing CLT as a theoretical framework for instructional strategies in engineering education. For instance, Rathnayaka et al. investigated the use of pre-lab online learning resources to manage the cognitive load of engineering students in a thermodynamics course [15]. Mayer and Moreno [16] demonstrated that presenting engineering animation narration visually as on-screen text increased extraneous load compared to auditory narration. Furthermore, Chen, Chang, and Chuang [17] found that VR also affects cognitive load. However, measuring intrinsic load remains an ongoing challenge in applying CLT, and further research is needed to evaluate more granular differences among CLT-based instructional techniques [8].

The study provides insights into the mathematical modeling aspect of pre-college engineering education research. However, it is crucial to acknowledge its limitations. Firstly, the sample size was limited to students from only two schools, highlighting the necessity for future studies to encompass a more diverse range of educational contexts. Additionally, reliance on self-reported data from students suggests the potential benefit of employing mixed methods approaches. By integrating cognitive load measurements, comparative experiments, and observational data, a more comprehensive understanding of the topic could be achieved.

In conclusion, this study provides characteristics of mathematical modeling in high school engineering curricula. It also offers suggestions on instructional strategies grounded in CLT. Recognizing the impact of high school modeling activities holds significant importance for advancing engineering education. These insights have the potential to reshape pre-college engineering programs, foster the learning and teaching processes, and enhance students' skills for their future careers.

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Appendix A

17 Instructional Effects Due to Variations in Extraneous Cognitive Load

NO.	Effect	First Publication Year
1	Goal-free effect	1982
2	Worked example effect	1985
3	Completion problem effect	1987
4	Split-attention effect	1988
5	Redundancy effect	1991
6	Compound: Element interactivity effect	1994
7	Variability effect	1994
8	Modality effect	1995
9	Self-explanation effect	1998
10	Imagination effect	2001
11	Isolated elements effect	2002
12	Compound: Expertise reversal effect	2003
13	Compound: Guidance-fading effect	2003
14	Collective working memory effect	2009
15	Compound: Transient information effect	2011
16	Human movement effect	2012
17	Compound: Self-management effect	2012

Notes: The table is adapted from Sweller et al., 2019

Appendix B

The Codebook of the Paper

Coding Round	Code	Definition
1	Students make design decisions based on MATLAB	When working on an engineering project, students used information derived from MATLAB in coming up with solutions, designs, etc.
1	Students see the value of the MATLAB tool	Students showed that they understand at least some of the benefits of MATLAB.
1	Students did not see connection between computational and physical models	It was not evident to students how the work that students are doing in MATLAB translates to work in their physical engineering project, task, etc.
1	Challenge/Suggestion/Improvement	Any challenge, suggestion or improvement that students mentioned in their MATLAB activities.
1	Exploring MATLAB in depth	Students seem to go beyond just the activity's requirements to unpack MATLAB's "black box" or to see what else MATLAB can do
2	CLT- Intrinsic Load	Intrinsic load refers to the complexity of the information being processed and the knowledge to process that information.
2	CLT- Extraneous loads	Extraneous load is related to how information is delivered to learners.
3	Split-attention effect	Advocates consolidating disparate sources of information into a single location.
3	Self-explanation effect	Promotes replacing completed worked examples with prompts that prompt learners to self-explain the provided information.
3	The variability effect	Proposes substituting tasks that are similar with tasks that differ to enhance the transfer of learning.
3	The modality effect	Suggests replacing a unimodal configuration consisting solely of written text with a multimodal setup integrating spoken and visual information for improved learning outcomes.