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Challenges to Systems Thinking and Abstract Thinking Education During the COVID-19 Pandemic*

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Engineering, and especially hardware and software engineers, need systems thinking and abstract thinking mindset. Hands-on interactive assignments utilizing a combination of hardware and software have been shown to be the most effective methods of teaching systems thinking and abstract thinking. Nevertheless, this environment was shattered by the arrival of the COVID-19 pandemic, creating a number of challenging situations. During the pandemic, remote learning and social distancing posed the biggest challenges. Educators faced a challenge when creating hands-on and laboratory-based classes, and were forced to use innovative methods like virtual laboratories online. The research described in this paper examined the effect of changes to the educational environment caused by the COVID-19 pandemic on students' cognitive abilities development related to systems thinking and abstract thinking education. The study, which used quantitative and qualitative tools, involved 70 senior high school electronics students. According to the findings, there was a significant drop in both skills among remote group students in comparison with face-to-face group students. This study found that students are incapable of adapting to change in instruction modes if not given sufficient time, support, and communication.

Keywords: systems thinking; abstract thinking; engineering projects; electronics students; distance learning

1. Introduction

As engineering projects move to a higher level of complexity, educators continue to find new elements to improve the preparedness of future STEM professionals, especially engineers. This includes teaching students the appropriate thinking skills such as systems thinking and abstract thinking to enable them to toggle such challenges. Many literature reports have shown that systems thinking and abstract thinking are important thinking skills for engineers dealing with various levels of complex projects [1, 2]. Considering a system holistically, including the interrelations between systems components, as well as the relations between the system and its surroundings is known as systems thinking [3]. This approach allows handling the system and its components in a realistic context with a balanced attention paid to each and all subsystems and individual components. Meanwhile, abstract thinking is as critical to handle complex systems because it brings focus to details applying to the current level of complexity or viewpoint without distraction by less significant details at that particular level [3, 5]. Therefore, introducing these thinking skills to students, as early as high school years, should enrich their cognitive abilities resulting in improved performance and consequently motivating them to take on more challenging problems and projects as well as to venture outside the box.

Based on these findings, systems thinking and abstract thinking were integrated into hands-on activities and implemented amongst high school students. These hands-on activities were enhanced with dedicated assignments, which were scaffolded to formulate a complete course project. The idea was to train students on using these two thinking skills; then test changes in their performance while they extrapolate this knowledge to solve a fresh problem or carry out a fresh engineering project combining software and hardware [6]. However, the unexpected arrival of COVID-19 pandemic introduced a completely new challenge, motivating this study. This study aims to examine the effect of such sudden change on the development of students' cognitive abilities related to systems thinking and abstract thinking. The study included research into the effect of the infrastructure or environment of learning on the educational process through the change in students' performance when learning system and abstract thinking, which are embedded in experiential learning.

This paper includes a description of the theoretical framework furnishing the base for the research, which is looking at students' cognitive abilities' development in relation to systems thinking and abstract thinking through experiential learning while considering the influence of remote learning and social distancing dictated by the COVID-19 pandemic. Consequently, the research

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questions are formulated, and the study is conducted based on the described research methodology. Results are presented and discussed for insights from this experience highlighting recommendations related to the process of cognitive abilities development within the context of a challenged experiential learning.

2. Systems Thinking and Abstract Thinking

Systems thinking provides the foundation for systems engineering where it interconnects the different parts of a system as well as the entire system to the surrounding environment. Systems thinking is also important for aligning teams, disciplines, specializations, and interest groups. Therefore, a successful system engineer must have a capacity for engineering systems thinking [7, 8]. It is to be noted that successful systems thinking and system thinkers differ in their degree of achievement due to the possession of individual characteristics and personalities that enable some to perform system thinking more effectively than others [8]. This is especially needed when trying to solve an engineering problem rationally and efficiently, with traceable and justifiable decisions. With this balanced and holistic approach every component and subsystem will receive adequate attention and resources [9].

Cognitive characteristics of systems thinking enable better understanding of system functionality with lesser details, better understanding of the interrelationships between subsystems and components of the system, and improved consideration of the bigger environment of an engineering endeavor by way of integrating elements such as ethical, economical, and societal impact. Improved capabilities are also characteristic of systems thinking resulting in increased efficiency of the different steps formulating the system design process such as analyzing requirements of the system, producing design concepts, performing functional analysis, and optimizing the final system. In addition, systems thinking advances interpersonal skills such as improved teamwork contribution and leadership due to the improved understanding of one's role in the bigger picture, or comprehensive systems thinking. Therefore, numerous efforts have been reported in the literature showing the process of integrating systems thinking in educating engineering students at different levels and the effectiveness of such efforts. One of the main conclusions of these studies indicates that systems thinking is best developed in a team setting through active learning [10].

The ability to zoom in and consider the details of a certain level or complexity in a project or a certain component while ignoring less significant details requires abstract thinking [5]. A system can be handled at different levels of abstractions enabled by abstract thinking where the attention to details is maximum at the lowest level then it decreases as the abstraction level moves closer to the complete system level [11, 13]. This capacity is critical in engineering systems, especially software design and analysis. Therefore, abstract thinking education has also received significant attention resulting in numerous literature reports demonstrating its effectiveness in improving engineering students' cognitive abilities [14, 16]. Characteristics of abstract thinking are similar to those of systems thinking where cognitive abilities, capabilities, and interpersonal skills are improved when learning and implementing abstract thinking. Moreover, it has been shown that the most effective vehicle to learn systems thinking and abstract thinking is hands-on or interactive assignments that combine hardware and software [6].

It is important to note that due to the moderately significant correlation between systems thinking and abstract thinking [6], they can be learned in the same setting. Meanwhile, differences in performance students are expected to persist due to individual backgrounds and interpersonal skills.

3. The Learning Environment

Numerous literature reports show maximized effectiveness of systems thinking and abstract thinking education during active learning or hands-on activities such as what constitutes an engineering project. This makes the learning pedagogy and environment a critical part of the educational process. Projects are usually carried out by teams of students working through a series of assignments. This involves interactions with instructors and colleagues in different forms supporting a continuous motivation and thrust to accomplish among the students. However, a sudden disruption to this environment took place with the arrival of the COVID-19 pandemic, causing many unprecedented challenges. Many literature reports have already pointed out the particulars of these challenges and attempted measurements of their effect on students' performance and the entire educational process [18]. The main challenges related to the pandemic were related to remote learning and social distancing. As a result, a variety of modes of instruction were attempted to circumvent the challenges posed by the pandemic and replace the face-to-face mode of education. These include synchronous and asynchronous video classes which were somewhat successful in delivering lecture-based classes. However, for hands-on and laboratory-based classes, the challenge persisted and forced educators into the unchartered territories of innovative methods such as online virtual labs and labs conducted by one team members while the rest of the team watches from far through a camera [19, 20]. Despite the variety of creative modes of delivery used by educators, and the levels of success achieved, many challenges emerged and influenced students' performance. These challenges ranged from variation in computer skills among instructors to students' access to reliable connections and digital equipment. It also included the reduced or lack of interaction among students and reduced interaction with instructors [20]. Social isolation itself caused another set of challenges such as increased anxiety and stress levels among students [21]. Consequently, the final effect trickled to students' motivation levels which are interconnected with their level of learning effectively.

It is to be noted here that involvement and connection to the university have been reported as critical elements to students' motivation. Therefore, different levels of motivation can be found between groups of students who studied in face-to-face mode, started with face-to-face and moved to distance learning, or started studying in distance-learning mode from the beginning. Experience with the arrival of the pandemic and how such a sudden change affected the educational process shows that learning environments, systems, and processes, need a serious review to improve their resilience against similar changes [21, 22].

4. Research Goal and Questions

The purpose of this study is to investigate the effect of changes to the educational environment caused by the COVID-19 pandemic on students' cognitive abilities development related to systems thinking and abstract thinking education. This education is conducted using hands-on activities which are scaffolded to formulate a complete engineering project. The population of students receiving this education includes senior high school students. The research question formulated was as follows:

What was the effect of the COVID-19 pandemic on students' cognitive abilities' development related to learning systems thinking and abstract thinking?

5. Methodology

5.1 Participants

The study involved 70 senior high school students studying electronics as part of their curriculum and divided into two groups. One group included 36 students who were studying in a face-to-face setup, before the pandemic, during year 2019. The other group included 34 students who were studying online with social distancing applied because of the pandemic during year 2020. Both groups of students had characteristics similar to normal senior high school students.

5.2 Intervention

For both groups, systems thinking and abstract thinking education were carried out using a set of scaffolded assignments constituting a complete project. Students were divided into teams of two in each group. The project was initiated by each team within a group as a proposal to the instructor and a final report was required of each team at the end of the semester.

Both, the face-to-face (F2F) group, and the online (Remote) group, were required to design and implement a system combining hardware and software, based on an Arduino micro-controller board (programmable device). Throughout the project, more hardware components were added gradually, and later tested using electronics measuring equipment (e.g., oscilloscopes and multi-meters). Examples of these components include sensors, motors, and displays, to name a few. Fig. 1 shows an example of a final project outcome which is a baby-food production system.

The difference in experience between the two groups of students is that the F2F group was able to conduct the work on physical systems in the laboratory and with their teammates. The Remote group worked with virtual products based on a virtual Arduino simulator within the software PROTEUS®. The virtual products (simulated by PROTEUS) included virtual hardware components, such as sensors, motors and displays, as well as electronics measuring equipment (e.g., oscilloscopes and multi-meters). Fig. 2 shows an example of a final virtual project (simulated) of a baby-food preparation system.

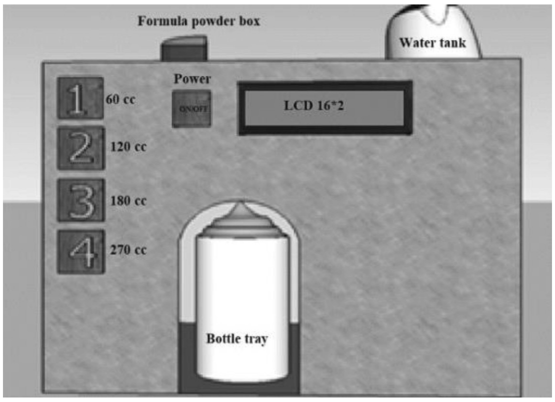

Fig. 1. Design of a smart baby formula maker.

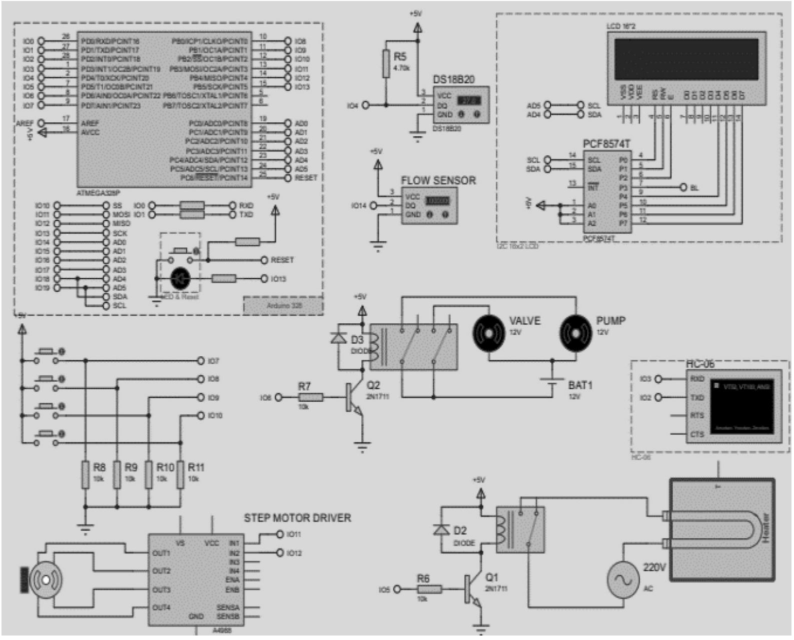

Fig. 2. Simulation of a smart baby formula maker using PROTEUS.

Table 1. Sample assignmnets of systems thinking and abstract thinking

Name (skill)	Essence	Systems thinking	Abstract thinking
Formulating requirements	Students are required to formulate project and software requirements	Understanding of project requirements	Understanding project software requirements and understanding software implementation requirements
Suggesting several alternatives for implementing the project and choosing the optimal alternative.	Each team of students offers at least 3 solutions (alternatives) for implementing the project. Then, the students in each team compare the alternatives and choose the optimal alternative.	Providing several alternative solutions and choosing an optimal alternative in systems thinking among	———————
Build a block diagram and analyze the principle of operating system chosen for implementation.	Students are required to: • To Build a block diagram of the proposed system. • Analyze the principle of the selected system's operations for implementation.	Overall understanding of the project, understanding the interrelationships between the system components, functional analysis of the chosen alternative and understanding the synergy in the system	———————
Build the data flow diagram (DFD)	Students are required to: • Build a software data flow diagram (DFD). • Describe in their words the input information, information processing, output information) of the system.	———————	Building the data flow diagram (DFD) of the software
Build the structure chart of the software	Students are required to build a structure chart of the software (describe the purpose of the modules, routines, and their relations)	———————	Structure chart of the software

During the semester, 14 assignments dealing with systems thinking and abstract thinking were required and integrated to formulate the project. These dedicated assignments were based on the cognitive skills of systems thinking and abstract thinking. Table 1 displays samples of the assignments.

5.3 Procedure

The study included mixed methods drawing from instruments collecting both quantitative and qualitative data. During the school year, students in the F2F teams worked on hands-on projects that combined hardware and software in the F2F learning mode, while students in the Remote teams worked on virtual projects that combined hardware and software in the online learning mode. These projects consisted of fourteen assignments focused on systems thinking and abstract thinking were scaffolded and integrated to complete each project. At the end of the school year, students took an achievement test, which was designed to evaluate students' cognitive skills of systems and abstract thinking. In addition, at the end of the year, students submitted project final reports.

The quantitative data from the different instruments were analyzed using an independent samples t-test between the populations of the two groups. In addition, two experts in engineering education coded (labeling and organizing) the qualitative data (Students' reflections in final reports, as well as observations conducted by one of the study's authors while students work on their projects) and classified them into categories using directed content analysis to identify different themes and the relationships between them, based on the cognitive skills of systems thinking and abstract thinking adapted for high-school electronics' students.

5.4 Tools

The achievement test was based on analysis of a system opening and closing a parking lot gate. This system was not part of the final project for any of the teams. The test included 18 multiple-choice questions (one correct answer and three distractors), nine of the questions dealt with systems thinking and the other nine questions dealt with abstract thinking. The questions were of equal value. The test time was limited to one hour. Two experts in engineering education validated the test. To assess the quality of the test, two experts were consulted, who evaluated the test using a procedure known as expert judgement [23].

6. Findings

Table 2 shows students' mean score *M* (ranging between 0 and 100) and standard deviation *SD* from both, Remote group, and F2F group.

An independent samples t-test revealed a significant difference in students' systems thinking scores between the Remote group and the F2F group $t(49.98) = 6.63$, $p < 0.001$; a significant difference in abstract thinking scores between the two groups $t(68) = 7.16$, $p < 0.001$.

Analysis of the qualitative data (final reports and observations) reveals that the Remote group had additional skills difficulties (relative to F2F group) in systems thinking and abstract thinking assignments as shown in Table 3.

To explore the reasons for the students' challenges in performing their projects, a qualitative instrument was employed by exploring the reflections from the students' final reports which was a

Table 2. Descriptive statistics of systems thinking and abstract thinking from both F2F and Remote projects

		Systems thinking		Abstract thinking	
Group	***N***	***M***	***SD***	***M***	***SD***
Remote projects	34	38.17	22.31	37.91	16.90
Face-to-face projects	36	66.80	12.00	66.54	16.57

Table 3. Systems thinking and abstract thinking difficulties among students

Skill difficulty	Systems thinking	Abstract thinking
Problems solving in implementing the solution	*"I always asked my instructor to help me to figure the problems out"* *"I faced many problems in hardware within PROTEUS and couldn't solve them."*	
Using simulation	*"We encountered some problems and difficulties related to the components of PROTEUS."* *"It was so difficult to run the project through simulation because the components were not compatible with the practical components."*	
Build the data flow diagram (DFD) of the software		*"Most students asked the instructor for help in building the DFD of the software"* *"Most students had difficulties to explain the DFD of the software"*
Build the structure chart of the software		*"Most students had difficulties in building the structure chart of the software and corrected the charts after the teacher's help"* *"Most students had difficulty to explain the structure chart"*

Table 4. Students' challenges in performing their projects

Item	Challenges
Connection to the internet / Infrastructure	*"It is hard to work on the project by zoom because of the bad connection"* *"It's boring to work on the project by simulation without hands-on components"* *"The internet connection is bad"* *"I have no WIFI in the neighborhood"*
Interacting with other students / Teamwork	*"It's hard to make assignments online with the partner"* *"It's hard to chat with my partner (without a microphone)".* *"My partner does not help me with the project assignments because he claims he does not have internet at home"*
Interact and communicate with instructor / Live-interaction	*"The instructor needs some training on using zoom tool"* *"Some students do not respond when the instructor asks them probably because they are asleep"* *"Most students do not agree to open cameras and some claim they do not have microphones"*

required part in the report. Students were asked to describe, in their own words, the most challenging issues they faced during the COVID19 Pandemic. These results were coded and classified according to the three categories shown in Table 4.

7. Discussion

Results collected and presented in the findings' section show that systems thinking, and abstract thinking can be taught together using a hands-on vehicle such as structured engineering projects with dedicated assignments. These results also show that the learning environment, especially infrastructure readiness and flexibility, play a significant role in the effectiveness of this learning process. This was evident in observations and students' reports, summarized in Table 3. These comments express results of the rapid change in mode of instruction from F2F to Remote during the COVID-19 pandemic which did not allow sufficient preparation or training time for both students and instructors. These results confirmed the quantitative results shown in Table 2 which were produced using an independent exam that focuses on measuring cognitive skills related to systems thinking and abstract thinking. These results show a proportional drop in both skills between students in the F2F group and those in the Remote group. As a side observation, the proportional drop proves also that both system and abstract thinking are interconnected and confirms that teaching them simultaneously is the efficient way to go.

To further explore the reasons for this deterioration in learning systems thinking and abstract thinking during the pandemic, students' reflections were also collected and analyzed. Table 4 includes a summary of these reflections which were categorized under three categories: Infrastructure, teamwork, and live interaction. Flexibility and availability of the technical infrastructure and related support had a clear influence on the quality of the experience which directly affects motivation and sustainability. Teamwork and the ability to interact with colleagues was also influential on motivation and quality of performance. Live interaction with instructors allowed for an extended attention span by the students and faster response time to bring them back to the flow and exchange of information raising the levels of motivation which was reflected on the quality of performance. These three categories are critical to motivation which has a significant role in improving students' learning and comprehension. It is evident from the finding that a significant difference (retraction) in students' performance scores was realized by the Remote group which was learning during the COVID-19 Pandemic compared to the F2F group. The COVID-19 Pandemic adversely affected students' systems thinking and abstract thinking development and performance.

8. Conclusions

This study was set out to explore the impact of changes in education environment and instruction mode caused by the COVID-19 pandemic on cognitive skills of systems thinking, and abstract thinking. In general, results of this study agree with the literature regarding systems thinking, and abstract thinking interrelation and best practices such the best vehicle to teach them both being a hands-on activity, particularly structured engineering projects. Moreover, these two thinking skills can be taught simultaneously using the same project, or hands-on activity.

Meanwhile, hands-on activities, and experiential learning in general, are dependent on the infrastructure available, its readiness, and its level of flexibility. Results of this study revealed that students are not capable of adapting to change in instruction modes if not given the appropriate time, support, and communication. Moreover, access to advanced equipment and technological availability, combined with innovative instruction can actually bring significant flexibility and resilience to this education process. In addition, students expressed dissatisfaction with the loss of interaction with colleagues.

Remote communication can help ease some of these challenges, but it will not completely solve the problem. These factors combined directly influence the motivation of the students and have a remarkable impact on their performance and achievements. Results of this study give new insights on system thinking and abstract thinking education effectiveness among younger generations of students, with realistic extraordinary circumstances, which allow insightful and improved design of educational material instilling thinking methods at early stages of education with an element of resilience towards uncertainty of the educational mode or the surrounding environment.

References

1. S. Grover and R. Pea, Computational thinking in K–12: A review of the state of the field, *Educational Researcher*, **42**(1), pp. 38–43, 2013.
2. S. Nagarajan and T. Overton, Promoting systems thinking using project- and problem-based learning, *Journal of Chemical Education*, **96**(12), pp. 2901–2909, 2019.
3. P. M. Senge, *The fifth discipline: The art and practice of the learning organization*, Doubleday, New York, 1990.
4. L. Bertalanffy, *General system theory*; George Braziller Inc.: New York, NY, USA, 1968.
5. B. Timothy, *Introduction to object-oriented programming*, Pearson Education, India, 2008.
6. A. Shekh-Abed, Systems Thinking and Abstract Thinking among High-School Students Executing Projects Combining Hardware and Software, Ph.D. thesis, Technion – Israel Institute of Technology, 2020.
7. J. M. Brooks, J. S. Carroll and J. W. Beard, Dueling stakeholders and dual-Hatted Systems Engineers: Engineering challenges, capabilities, and skills in government infrastructure technology projects, *IEEE Transactions on Engineering Management*, **8**(3), pp. 589–601, 2011.
8. M. Frank, Assessing the interest for systems engineering positions and other engineering positions' required capacity for engineering systems thinking (CEST), **13**(2), *Journal of Systems Engineering*, pp. 161–174, 2010.
9. A. Kossiakoff, W. N. *Sweet*, *Systems engineering principles and practice*. Edited by A. P. Sage. 2nd ed, Willey Series in Systems Engineering and Management. Hoboken, N.J: Wiley-Interscience, 2011.
10. H. L. Davidz and D. J. Nightingale, Enabling systems thinking to accelerate the development of senior systems engineers, *Systems Engineering*, **11**(1), pp. 1–14, 2008.
11. B. Liskov and J. Guttag, *Abstraction and specification in program development*, MIT press, Cambridge, 1986.
12. J. Sanguinetti, Abstraction and standardization in hardware design, *IEEE Design and Test of Computers*, **29**(2), pp. 8–13, 2012.
13. N. Ye and G. Salvendy, Expert-novice knowledge of computer programming at different levels of abstraction, *Ergonomics*, **39**(3), pp. 461–481, 1996.
14. S. Grover and R. Pea, Computational thinking in K–12: A review of the state of the field, *Educational Researcher*, **42**(1), pp. 38–43, 2013.
15. V. Barr and C. Stephenson, Bringing computational thinking to K-12: What is Involved and what is the role of the computer science education community? *ACM Inroads*, **2**(1), pp. 48–54, 2011.
16. H. Koppelman and B. van Dijk, Teaching abstraction in introductory courses, *Proceedings of the Fifteenth Annual Conference on Innovation and Technology in Computer Science Education*, ACM, pp. 174–178, 2010.
17. N. Barakat, A. Al-Shalash, M. Biswas, S. Chou and T. Khajah, Engineering experiential learning during the COVID-19 pandemic, *ICL 2021, 24th International Conference on Interactive Collaborative Learning, Dresden*, Germany, Sep. 2021.
18. M. Marek, C. Chew and W. Wu, Teacher experiences in converting classes to distance learning in the COVID-19 pandemic, *International Journal of Distance Education Technologies*, **19**(1), pp. 89–109, 2021.
19. A. Shekh-Abed and N. Barakat, Challenges and opportunities for higher engineering education during the COVID-19 Pandemic, *International Journal of Engineering Education*, **38**(2), pp. 393–407, 2021.
20. A. Aristovnik, D. Keržič, D. Ravšelj, N. Tomaževič and L. Umek, Impacts of the COVID-19 pandemic on life of higher education students: A global perspective, *Sustainability*, **12**(20), pp. 8438, 2020.
21. R. Raaper and C. Brown, The Covid-19 pandemic and the dissolution of the university campus: Implications for student support practice, *Journal of Professional Capital and Community*, **5**(34), pp. 343–349, 2020.
22. M. Olmos-Gómez, Sex and careers of university students in educational practices as factors of individual differences in learning environment and psychological factors during COVID-19, *International Journal of Environmental Research and Public Health*, **17**(14), p. 5036, 2020.
23. S. G. Sireci, The construct of content validity, *Social indicators research*, **45**(1), pp. 83–117, 1998.

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