Improving engineering students' problem-solving skills through think-aloud exercises

Huihui Qi, Alex Phan, He Liu, Marko Lubarda, Maziar Ghazinejad, Xuan Gedney, Rufu Gong, Haojin Chen
University of California, San Diego – La Jolla, CA, USA
Emails: {huqi, mgphan, hel119, mlubarda, mghazinejad, xgedney, rug004, hachen}@ucsd.edu

***Abstract*—This paper presents an innovative approach to improve engineering students' problem-solving skills by implementing think-aloud exercises. Sometimes engineering students claim they do not know where to start with the problem-solving process, or they are not sure how to proceed to the next steps when they get stuck. A systematic training that focuses on the problem-solving process and the justification of each step could help. Think-aloud techniques help make the invisible mental processes visible to learners. Engineering think-aloud technique engages students and helps them make their way through a solving process step-by-step, reasoning along with them. In this study, a multiple faceted systematic approach that integrates think-aloud exercises through video assignments and oral exams were developed and implemented in two pilot engineering classes. We present our think-aloud exercises and oral exams structures in each of the courses and their impacts on students' learning outcomes, and students' perceptions towards the pedagogical approach. Both quantitative and qualitative results show that the think-aloud exercise assignments and oral exams enhance students' problem-solving skills and promote learning.**

Keywords—think-aloud technique, video assignment, oral exams, engineering education.

I. Introduction

It is without any doubt that problem-solving skills are critical to engineering students. However, engineering students sometimes claim they do not know where to start to solve a problem, or when they get stuck with the problem-solving process, they are not sure how to proceed to the next steps. A systematic training that focuses on the problem-solving process and justification of the decision making process of each step could address such challenges in students' learning. Exercises that require students to think aloud and verbalize their understanding could help learners to trace their thought process and identify gaps in understanding.

Concurrent verbalization is a defining characteristic of think-aloud protocols, which have been extensively used in psychological and educational research, including research into information processing, problem-solving, decision making, and other tasks [1-7]. Though the protocols have emerged as a scientific method for data acquisition from human subjects in disciplinary research, their application has extended into pedagogical practice where they are used to assist the development of students' problem-solving skills and their ability to learn more effectively and efficiently [6-10]. Think-aloud exercises have been adopted in courses in mathematics and other subjects to help guide students' self-reflective actions and the self-regulation of learning [6-13]. During an educational think-aloud session, the student articulates their thoughts orally as they work toward comprehending presented material or solving an assigned problem. Prompts, typically administered by the instructor to the student, serve to direct the student's cognitive processes toward higher-order reasoning, reflection, and regulation of their problem-solving approaches. Evidence suggests properly structured think-aloud activities help students improve their metacognitive abilities and their skills in navigating complex issues and environments [3,6,8,12]. Think-aloud sessions also serve as a diagnostic tool to the instructor, offering them valuable insights into how the student manages and applies their knowledge in problem solving [13-19]. In this sense, think-aloud based assessment like oral exams allows the instructor to adaptively probe into the deeper layers of a student's understanding, identify misconceptions as well as weaknesses in a student's thought process, and to immediately intervene to help the student rectify their mistakes, explore better ways to apply their knowledge, and become more aware of improved lines of reasoning. Regularly integrated think-aloud exercises inspect a student's mental models and promote the student's metacognitive behaviors, and think-aloud-based assessments like oral exams are geared toward assessing a student's understanding of concepts and relationships among them. Think-aloud exercises are also naturally adaptable to cooperative settings, where multiple students work together on a common task while communicating and thinking aloud, providing feedback and challenging each other [12]. Research indicates that accelerated development of metacognitive and problem-solving abilities may be expected in students partaking in cooperative think-aloud exercises owing to the peer learning environment and concomitant social interactions implicit in such a design [12-14].

In this research, a think-aloud-based exercise and assessments structure was developed and implemented into two pilot classes in Mechanical Engineering and Electrical Engineering: a foundational engineering mechanics - Statics and Dynamics class and a upper division project based LabVIEW programming class. The multi-faceted think-aloud exercises and assessments include two main elements: video assignments and oral exams. To better facilitate the video assignments, the Statics and Dynamics class also added guidance prompts to written homework questions and set up the video assignment as group discussion-based. All of the elements emphasize on the verbalization of the key concepts behind the problem-solving and decision-making process.

The researcher aims to evaluate the impact of the think-aloud exercise and related assessment on students' learning. Students' perceptions and direct learning outcomes data (such as exam grades and other class performance scores) were analyzed, using various methods including qualitative coding analysis, statistical descriptive analysis, and inferential statistical analysis. The results show that the think-aloud exercise assignments and oral exams enhance students' problem-solving skills and promote learning.

II. Methodology

The think-aloud exercises were developed and implemented in two pilot courses: a lower-division Statics and Dynamics engineering course of 110 with primarily sophomores, and an upper division hands-on LabVIEW programming course of 24 students, primarily juniors and seniors. Each course designed and implemented video assignments and oral assessment as the cascading two scaffolds think-aloud exercise implementation. It is designed with the hope that the think-aloud exercise in homework will help students to build the problem solving skills by constantly checking and "speaking out" their thought process, and the oral exams serves as a tool to check their progress. The skills learned and enhanced in assignments and oral exams improve students' problem solving skills. The format and structure of the think-aloud exercise were designed differently for the two courses to best fit the course content and structure. The details are elaborate in this section.

A. Think-Aloud Exercise in Homework Assignments

In the Statics and Dynamics engineering course, guidance prompt questions were provided to students for each written homework assignment. Students are supposed to use these guidance prompts to formulate problem-solving strategies. The guidance prompts are written in a way that if students are able to answer all of them correctly, they are supposed to be able to formulate the problem-solving process for the problem and other problems that need similar concepts. The prompt questions also promote the students to think about the general concepts behind a specific calculator process, and to minimize the "plug and chug" from similar examples. Students use these prompt guidance to think-aloud and verbalize the problem solving process and the concept behind it for the video assignment.

To enhance this think-aloud learning activity and provide an opportunity to receive feedback on their thought process, the video assignment was designed to be group based. The students were asked to hold discussions in a group of 3 students. They take turns to lead discussion for at least one question in the group discussion and submit a video for extra credits. Students who do not participate in such group discussion and submit video assignments still need to answer the guiding questions as part of their written assignments.

The discussion starts from one question led by the question leader, the rest of the group actively provide feedback and raise questions. Once done with one question, another student will lead the discussion for the next question, until everyone in the group has the chance to lead at least one discussion. The discussions are encouraged to be centered around "guidance prompts" that were given for each problem, but not limited to it. Each written homework problem was accompanied by a set of guidance questions. These guidance questions provide the students with a checklist and hints on how to solve the problem and contain suggestions on "think-aloud" techniques for better conceptual mastery of the knowledge. Students are encouraged to answer these guidance questions aloud before they start the computational process to aid in their understanding of the reasoning behind the calculation process. Homework grading was based on both answers to the guidance prompts and problem-solving process. The students are also encouraged to thoroughly review the questions, then hold the group discussion meeting before they solve all problems in detail, so that they could validate their correct problem-solving strategy. Whenever the group gets stuck in discussion, we encourage them to review the lecture and discussion materials for reference. If after a thorough discussion, the group is still unable to arrive at the solution or is not sure, students are encouraged to attend office hours. A sample group discussion video was provided to the students. Students were encouraged to share screens to present the problem they were discussing and use the annotation tools as needed.

In the upper-division LabView programming course, video assignments were assigned as a part of weekly students' homework. To complete the assignment, each student was required to turn in a 4-minute video recording. Students were given a scenario with potentially multiple solutions and must narrow down on the best practice or approach and justify their reasoning within the video. To prepare for this assignment, students must think-about the solution and how to explain their thought process in a concise and succinct manner. Retakes during recording allow students to think-aloud and synthesize their understanding in a coherent and well-articulated manner. Students typically have the flexibility of weighing the pros and cons of a particular solution and discussing potential alternative solutions. This process inherently provides an opportunity for students to say the same concepts in different ways, priming synthesis and rationale. Students' video recordings are evaluated based on completeness and students' explanation of the concepts. The teaching team would provide a short written feedback for each submission to help students improve their answers and promote follow up questions from students.

B. Oral Assessment

The second part of the think-aloud exercise is to implement oral exams to the classes. The courses studied in this paper were conducted in either remote or hybrid mode. Thus, the oral examination was conducted over Zoom where assessors and the testing student were in a Zoom room and students were allowed to utilize the white board, annotation function, or share screen capability to assist with presenting their answers.

In the Statics and Dynamics course, the oral exam was conducted as part of the quizzes (10% of the overall course grade). Each student was asked to solve a problem during the 15 minutes session with either the instructor or instructional assistant. Each student has a different version of the question and the problem complexity was calibrated. In the oral assessment, students were given a list of 3-5 guiding questions similar to the homework assignment. Students walked through their problem-solving process by addressing the think-aloud prompts and explained the reasoning behind each decision. If students get stuck, hints were provided to help students to move to the next step. This will allow the students to demonstrate a full picture of their knowledge. Often in written exams, students were not able to move forward when getting stuck at a critical step. Feedback was given during the oral exam and grading was based on a predetermined rubric (0-5 scale) that assesses the correctness and reasoning of their answer.

In the LabVIEW programming course, the oral exams were conducted as part of the midterm assessments. Each oral exam was worth 30% of the midterm grade (3% of the overall course grade). Each student was given a design prompt with specifications and asked to perform live coding to solve the problem within a 10-minute time slot. Students were instructed to go over the main steps and list out the main concepts before starting the coding process. Students were also asked to think-aloud as they solve the problem, discussing the rationale behind each of the elements that they decide to use to satisfy the design requirements. Hints were given as needed but the students were given a chance to do as much on their own as possible. The work of the students were evaluated based on the predefined rubric (0-10 scale) to assess both correctness of the answer and rationale behind design choices. The assessors provided a brief feedback at the end of the assessment and showed the student the sample solution if they were not able to fully answer the question. This last step was essential for the teaching team as well as the students to identify and address any knowledge gap.

Table I and II demonstrate a sample for video assignments and oral exams for the Statics/ Dynamics and Labview Programming classes respectively.

TABLE I. STATICS/DYNAMICS CLASS: SAMPLE VIDEO ASSIGNMENT AND ORAL EXAM QUESTION

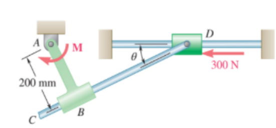
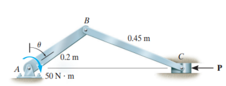
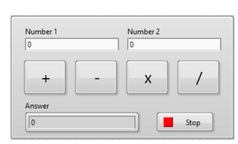
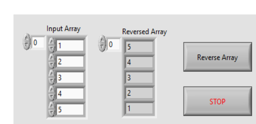
	Static/Dynamic Class Sample questions	
	Homework assignment	***Oral Exam***
Problem Description	 Rod CD is attached to the collar D and passes through a collar welded to end B of lever AB. Neglecting the effect of friction, determine the couple M required to hold the system in equilibrium when $\theta = 30^\circ$. Please answer the prompt questions before you solve the problem in detail numerically.	 The constant moment at A is applied to the crankshaft. Surface at C is frictionless. We are interested in determining the compressive force P that is exerted on the piston to maintain equilibrium. Please walk through your problem-solving steps without worrying about numbers.
Guidance Prompt Question	—To hold the system in equilibrium, what conditions must be satisfied? —What object (s) should we choose to draw the FBD? How many FBD do we need? Should we treat the object as a rigid body or particle? —What supports are applied to the object? What reactions do the support provide? —For each FBD, what equilibrium equations can we get? Can we solve this problem based on those equations?	—What object(s) should you consider for a free-body diagram(s)? —Draw the FBD(s); what force(s) and/or moment(s) act on each object? —Explain the direction and magnitude where applicable. —What unknown quantities can you determine or relate from each FBD? How would you do this?

TABLE II. PROGRAMMING CLASS: SAMPLE VIDEO ASSIGNMENTS AND ORAL EXAMS QUESTIONS

	Programming Class Sample questions	
	Homework assignment	***Oral Exam***
Problem Description	Create a calculator in LabVIEW. Create a Front panel with two numeric inputs and the 4 basic mathematical functions (+, -, x, /). The VI should accept two numbers as an input and update the answer output when one of the operation buttons is pressed. Your calculator should continue running until the user presses a stop button on the front panel. Provide a brief 3-4 minute video discussing the reasoning behind your code structure and how the inputs are processed	Shown here is a program that reverses arrays. There will be an input array control, an output array indicator, a reverse button, and a stop button on the front panel. When and only when the user presses the button, the output array should display the reverse of the input array. The program should stop when the user clicks the stop button. Please share your screen, open a new VI and walk us through how you would program on the block diagram to accomplish this.
User Interface (provided with prompt)		

III. RESULTS AND DISCUSSION

In this study, to understand the impact of the think aloud exercises on students learning and students perceptions towards it, both quantitative and qualitative analysis were conducted, and key findings are discussed in this section.

A. Students Performance Analysis

Statics and Dynamics Course

To gauge the impact of the think-aloud exercise on students' learning outcome, students' oral quiz 1, oral quiz 2, midterm exam and final exam grades were investigated with the number of video assignments completed.

The correlations between video assignment submission and course assessment performance in the statics and dynamics course are shown below. Four assessments were given in the course in the following order: quiz 1 (oral assessment 1), midterm exam (written), quiz 2 (oral assessment 2), final exam (written). The video assignments in this course were mainly graded based on completion with spot checks due to limitations in instructional team availability, though in the future, detailed grading for these assignments may prove to be useful to gain better understanding of the benefit video assignments when students complete them at various levels of performance.

Fig. 1 Assessment performance as a function of video assignment submission.

In this analysis, students were separated into bins based on the number of video assignments submitted prior to each assessment, which is then compared to the average assessment score for each group. The data suggest that completion of additional video assignments in the course has a positive correlation with assessment (both oral and written exams) performance. Particularly later in the course, when the second oral assessment and the final exam were administered, the groups of students who have completed a significant portion of the video assignments (out of the total of 8 assignments) performed better on the assessments on average.

It is worth noting the correlation between students' cumulative GPA and their performance on assessments. Towards the end of the quarter, the groups of students with most video submissions have average cumulative GPA which show trends similar to their average assessment performance, as shown in Fig.2.

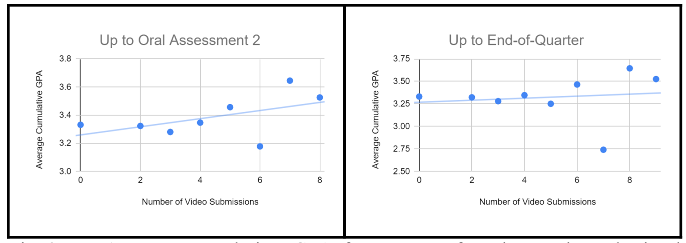


Fig. 2 Average cumulative GPA for groups of students who submitted specific numbers of video assignments prior to each late-quarter assessment. Note the similarities in shape to the average assessment performance (Fig. 1) for students with more than 4 video assignment submissions.

The effects of students' cumulative GPA were further considered in the following analysis. The data above was reconstructed to exclude students with extremely high and low GPAs. The resulting plots in Fig.3 account for students with cumulative GPA between 2.00 and 3.85, and they suggest that participation in video assignments may have a more significant impact on this group of students, with a slightly more pronounced positive correlation between video assignment submission and late-quarter assessment performance.

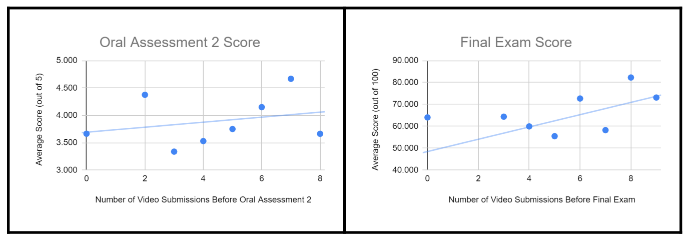


Fig. 3 Late-quarter assessment performance for students with cumulative GPA between 2.00 and 3.85.

For students with cumulative GPA between 2.00 and 3.85, a more pronounced positive correlation between video assignment submission and average assessment scores of each respective group can be observed. Through the exclusion of GPA extremities, the consistent participation in video assignments in the statics and dynamics course do exhibit potential to have positive impacts on students' assessment performance, for both written and oral assessment formats. Additionally, it was noted that there may be a positive correlation between students' performance on oral assessments and written exams, which further points towards potential benefits of verbal activities on student learning (Fig.4).

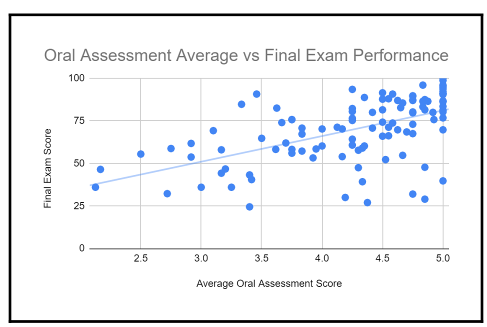


Fig. 4 Correlation between oral assessment and written assessment (final exam) performance.

LabVIEW Programming Course

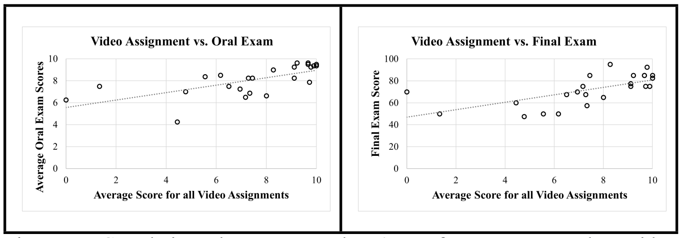


Fig. 5 Correlation between students' performance on the video assignments and their performance on the midterm (oral) and final (written) assessments.

The results (Fig. 5) showed that the average of the video assignments (n = 6) has a positive correlation with the average of the two oral exams (midterms) and the written final exam. The trend suggests that students who performed well on the video assignments tend to perform better on the exams, both oral and written forms.

Our observations show students who generally performed well on the video assignments demonstrated high efficacy in communicating their thought process, reasoning, and justification thoroughly and concisely. These students often included a logical explanation behind why certain processes, structures, or elements were selected to solve the problem. In contrast, students from groups who did not perform as well, often were able to solve the problem but could not explain their work thoroughly or in depth. For example, students who struggled were able to list steps taken and identify coding elements, but did not demonstrate conceptual understanding by providing their reasoning throughout the problem-solving process.

B. *Students feedback analysis*

The Students' perceptions were collected via surveys and studied about both the video assignments and oral exams. 71% (79 out of 110) of the Statics and Dynamics students took the survey, and 79% (19 out of 24) of the LabVIEW programming class took the survey.

For the Statics and Dynamics course, among the survey takers who completed various numbers of video assignments, based on likert-scale questions results, 75% of the students agreed or strongly agreed the video assignment helped them to gain a deeper understanding of the course materials. 78% of the survey takers agreed or strongly agreed that the oral assessment increased their understanding of the subject matter. 77% of the survey takers expressed that they wish their future engineering classes to implement oral assessment.

For the programming course, 90% agreed or strongly agreed that video assignments helped them gain a deeper understanding of the course material. 79% agreed or strongly agreed that the oral assessment increased their understanding of the subject matter.

Student responses to open-ended questions on the surveys provided richer information about their perceptions. Through coding analysis for the open-ended text question feedback, it is found that in general students reported very positive feedback of the think aloud exercise and assessment, consistent with the likert-scale question feedback.

For video assignments related comments, the frequency of "positive" codes in each course was higher than the frequency of the negative codes in each course respectively: The Statics and Dynamics class received 26 positive comments and 17 comments reporting issues regarding video assignments; and the LabVIEW programming classes received 9 positive comments and 7 reporting issues with their experience. Feedback from both classes expressed that the video assignments increased their understanding on the subject matter. Students reflected the video assignments helped them to organize their thoughts on the problem solving strategy before the actual problem-solving process. Some students from Statics and Dynamics classes emphasized the peer discussion around the think-aloud exercise helped them to gain new perspectives from peers due to the video assignments being group-based. And the group discussion also improved the productivity. The "negative" feedback from both classes are rooted in the logistical perspective of the video assignment rather than a problem with the content of the assignment itself. The most common logistical complaint mentioned in the student comments was that the assignment was time-consuming. From the instructor's perspective, this is not necessarily negative, as it was noticed before that many students were not taking advantage of the homework assignment opportunities to fully internalize the concepts in the homework, but rather try to quickly complete the questions. The video assignments "forced" the students to slow down and think about the reasons behind each decision they made to solve the problem.

For comments related to the oral assessments, in both classes, positive sentiments toward the oral assessments appeared more frequently in survey responses than negative sentiments—51 occurrences of positive sentiments for Statics/ Dynamics course and 20 for programming course, 25 negative sentiments/areas to improve for Statics/ Dynamics course and 19 for the LabVIEW Programming course. In addition to higher frequency, positive sentiments are also more rooted in the inherent nature of oral assessments, whereas negative sentiments are generally more directed toward factors that are often within the control of instructors and/or instructional teams. A number of students also identified improvements in their understanding of the course material as a result of oral assessments, which can once again be traced to the nature of such assessments of promoting students to think aloud and problem solving skills, receive real-time feedback to their problem-solving process, and focus on the conceptual generalizations behind solving a problem. It is worth noting that most of the negative sentiments were not targeted toward the nature of oral assessment, but about logistical factors that can be improved, such as short duration of oral assessment not providing sufficient time for students.

IV. Conclusions and Future Work

In this paper, we study the impact of think-aloud exercises in both homework and assessment on students' learning. The study is based on two pilot courses conducted at University of California San Diego in the Mechanical and Aerospace Engineering Department and the Electrical and Computer Engineering Department, respectively. In the courses studied, we adopt two formats for video assignments: individual response and group facilitated discussions. Positive correlations between the completion of video assignments and oral examination outcomes have been observed. Moreover, in terms of problem-solving abilities, students that performed well in video assignments were observed to have a higher efficacy in verbal communication of their reasoning and thought process.

Overall, the results from this paper underscore the importance of mindfulness and consciousness in the process of learning and building problem-solving skills. Within the context of oral examss, these video assignments lay the foundation for students to exercise their problem solving skills through think aloud methods. To better understand the impact of the video assignments on students' learning outcome, grading the video assignments based on performance rather than the completion will be helpful, and will be considered in the future research.

While the work in this paper provides a preliminary understanding of the positive impact of video assignments, future work to further refine the assignment format for such exercises may be necessary to achieve stronger correlations that are not influenced by students' varying motivation to achieve a higher grade. In addition, further studies would need to address the challenge of large class sizes in undergraduate engineering courses by proposing methods for group-format video assignments with the ability to discern individual conceptual mastery.

Acknowledgment

This material is based upon work supported by the National Science Foundation under Grant No. 2044472. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We thank the following colleagues for the helpful discussion and help provided during the planning and execution of the project: Dr. Saharnaz Baghdadchi, Dr. Nathan Delson, Minju Kim, Dr. Leah Klement, Dr. Mia Minnes, Dr. Celeste Pilegard, Dr. Josephine Relaford-Doyle, Dr. Carolyn Sandoval, Dr. Curt Schurgers. We are aslo grateful for the useful discussion with our project advisors: Dr. Christine Alvarado, Dr. Elizabeth Holcombe, and Dr. Adrianna Kezar, Dr. Sheri Sheppard.

References

[1] Fonteyn, M. E., Kuipers, B., & Grobe, S. J. (1993). A description of think aloud method and protocol analysis. Qualitative health research, 3(4), 430-441.

[2] Greene, J. A., Deekens, V. M., Copeland, D. Z., & Yu, S. (2018). Capturing and modeling self-regulated learning using think-aloud protocols.

[3] Banning, M. (2008). The think aloud approach as an educational tool to develop and assess clinical reasoning in undergraduate students. Nurse Education Today, 28(1), 8-14.

[4] Plumb, C., Marra, R. M., Hacker, D. J., & Dunlosky, J. (2018, June). Measuring engineering students' metacognition with a think-aloud protocol. In 2018 ASEE Annual Conference & Exposition.

[5] Güss, C. D. (2018). What is going through your mind? Thinking aloud as a method in cross-cultural psychology. Frontiers in psychology, 1292.

[6] Zbainos, D., & Touri, A. (2018). Formative assessment using the "think aloud" method for the development of executive functions and mathematical problem-solving ability. IJAEDU-International E-Journal of Advances in Education, 4(12), 298-306.

[7] Bowen, C. W. (1994). Think-aloud methods in chemistry education: Understanding student thinking.

[8] Raihan, M. A. (2011). 'Think-aloud' techniques used in metacognition to enhance self-regulated learning. Journal of Educational Research, 25(2), 125-160.

[9] Roberts, D. (2013). The clinical viva: an assessment of clinical thinking. Nurse education today, 33(4), 402-406.

[10] McKeown, R. G., & Gentilucci, J. L. (2007). Think‐aloud strategy: Metacognitive development and monitoring comprehension in the middle school second‐language classroom. Journal of Adolescent & Adult Literacy, 51(2), 136-147.

[11] Hartman, H. J. (2001). Developing students' metacognitive knowledge and skills. Metacognition in learning and instruction, 33-68.

[12] Zubaidah, A. M., Mr, W., & Mr, T. (2017, January). Metacognition Think Aloud Strategies In Setting Cooperative Think-Pair-Share/Square to Develop Student's Math Problem Solving Ability. In International Conference on Mathematics and Science Education (pp. 122-127). Atlantis Press.

[13] Du Toit, S., & Kotze, G. (2009). Metacognitive strategies in the teaching and learning of mathematics. Pythagoras, 2009(70), 57-67.

[14] Muijs, D., & Reynolds, D. (2017). Effective teaching: Evidence and practice. Sage.