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Resolving Troublesome Knowledge in Engineering Physiology using ICAP framework based Problem-Solving Studio

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Abstract
Analytical courses are often considered to be troublesome by students. In an attempt to get good grades, students overcome the learning gap by memorizing concepts or patterns that can solve similar problems. This approach leads to shallow learning due to non-student-centric teaching methods. Some methods such as flipped classrooms, clickers, and other active learning methods are shown to be effective. However, the impact of active and passive activities is considered less compared to interactive and constructive methods. To resolve troublesome knowledge found in an analytical course consisting of mathematical modeling, a problem-solving studio (PSS) micro-insertion was created and implemented. PSS is a highly interactive learning classroom environment based on student-student and student-instructor interaction. All the activities were designed to follow the interactive, constructive, active, and passive (ICAP) framework. A teaching assistant was stationed in the classroom to monitor students and map their movement across ICAP throughout this work. The activity aimed to improve the application of challenging concepts to solve problems and produce deeper learning. The students worked in groups with a common objective to find a solution for an open-ended question as they went through interactive activities. Groups of students indulged in assessing a scenario related to the technical concept, analyzed data, and formulated an alternative mathematical model to infer results. Results depicted a significant improvement in exam scores for the PSS group compared to the control. The PSS group also showed deeper learning of concepts and improvement in interactive and constructive skills. Teaching assistant observations indicated significantly more interaction during PSS activities compared to the control group. With the success of this PSS micro-insertion, it is aimed to convert the other troublesome knowledge areas into PSS for improved student learning.

Keywords: Problem-solving studio, troublesome knowledge, ICAP, cognitive learning, Enzyme kinetics

1. Introduction

Troublesome knowledge, as explained by David Perkins, can be categorized as ritual, inert, conceptually difficult or foreign [1]. Mostly, mathematical models and word problems can be categorized as ritual and conceptually difficult. This means students are focused on crunching numbers to match the final answer without having a deeper understanding of the concept. This can be attributed to the high-stake grade-driven environment of the lecture class, low cognitive learning environment or the difficulty associated with the concept of the mathematical equation [2]. Active problem-solving techniques implemented in a collaborative, low-stake environment can resolve the existence of troublesome knowledge in an engineering classroom. Hands-on projects, laboratory courses, video watching, note-taking, or use of clickers are successful class engagement active learning techniques [3]. However, these techniques promote manipulation of the instructional information but do not indulge in solving a problem by collecting new information. On the other hand, problem-solving studio (PSS), developed by Joseph M. Le Doux, places students in a cooperative environment encouraging interaction (with peers and professor) to solve complex problems [4]. In this work, PSS was implemented as a micro-insertion focused on enzyme kinetics and its application in the real world in an ‘engineering physiology' course. Traditionally, this topic has been a troublesome knowledge for the students as they are not able to understand the physical meaning of the Michaelis-Menton equation. The focus of this work was to understand the impact of PSS on student learning and their ability to interpret results after mathematical problem-solving. The interactive, constructive, active, and passive (ICAP) framework was applied throughout the module to quantify the levels of ICAP learning among the groups [5,6]. The ICAP framework hypothesizes that student learning follows the order of P<A<C<I focused activities. Studies conducted by Menekse et al. accepted the hypothesis that constructive activities result in better learning than active or passive activities. However, they did not find any significant difference in interactive and constructive learning [7]. A study designed to compare interactive and constructive learning outcomes showed that students who participated in group activities scored better in exams than those who completed their assignments individually [8]. Similar to literature, the work described below studied the impact of PSS on students' constructive and interactive skills while they worked on a problem based on troublesome knowledge.

2. Method

At Western New England (WNE) University, engineering physiology is a core course offered for biomedical engineering undergraduate junior level students. This course consists of biological concepts such as protein formation, enzyme-ligand binding, cell-signaling, muscle kinetics, and immunology, along with physiological mathematical modeling. Traditionally, mathematical models were routinely derived on a whiteboard while students actively copied them, and after derivation, the instructor would solve example word problems. This passive and minimally active practice have been insufficient in inculcating deep learning. To overcome this problem, a PSS module was created to compare the impact of interactive teaching on student learning outcomes. The control group (Fall 2020, n=30) was subjected to the conventional passive and active learning technique of copying notes during the class. The PSS group (Fall 2021, n=24) was introduced to various levels of active, constructive and interactive learning methods. The overall structure of the course was not altered in Fall 2021. Table 1 describes the changes introduced in Fall 2021 course to accommodate PSS.

It was hypothesized that: (1) use of PSS in the classroom can improve student learning outcomes, and (2) interactive and constructive learning method results in deeper learning. Student learning was tested by giving the same final exam question to the control and PSS group. The PSS group was evaluated on their ability to infer from new information using result reflection and online group discussion. Deep learning was assessed by comparing quiz (given within a week of PSS)

Table 1: Minor course changes incorporated in Fall 2021 to conduct PSS for four class hours.

Class hour	Fall 2020	Fall 2021
1	In-class lecture on cell structure	Homework reading: cell structure
2	In-class lecture on composition of cell	Homework reading: composition of cell
3	Enzyme kinetics word problem solving on board by the instructor	Substituted by PSS
4	In-class mid-term exam 1 review	Mid-term exam 1 review given as online quiz

and final exam scores (given 2 months after PSS). Further, the impact of PSS on students' constructive and interactive skills was analyzed using a self-assessment tool consisting of pre- and post-surveys. The surveys were approved by Institutional Review Board (IRB) prior to their use. Students' responses remained anonymous and were paired with the help of a random number. Each survey consisted of 5-choice Likert-scale questions (Table 2) rating constructive and interactive skills based on the student's experience. To assess the internal reliability of the constructive and interactive skill scales, the questions associated with each category were assessed using Cronbach's alpha test. A Cronbach's alpha greater than 0.7 was considered an adequate level of internal consistency for each measure within a category. After the pooled questions passed the Cronbach's alpha test, the averaged values for each category were compared. The pre- and post-survey data for each category was represented by means ± standard deviation and compared using a Two-Sample Student's t-test with a significance level, α=0.05. An observational assessment was conducted by a teaching assistant (TA). Throughout this study, a TA was in the classroom (Fall 2020 and Fall 2021) as a silent observer that noted the level of interactive, constructive, active, and passive learning. Both the teaching assistants, for control and PSS year, was trained to create an excel observation table throughout the study. They were asked to record time-dependent tally of the number of students involved in the ICAP per activity.

Table 2: Skill-based questions asked from students during pre- and post-survey.

Constructive Skills	**Interactive Skills**
Tests concepts quickly	Work creatively with others
Evaluate technical feasibility, societal benefits	Incorporate group input and feedback into the work
Elaborate and analyze ideas to improve creative effort	Working in a group with a mentor helped in completion of the project
Incorporate feedback effectively	Deals positively with praise, setbacks, and criticism
Utilize time and manage workload efficiently	created value for stake holders as a group
Monitor, prioritize and complete task without direct oversight	Development partnership and build a team
Explore and expand one's own learning to gain expertise	communicate an engineering solution in economic terms
Felt curious about the project	Create a model (equations) or prototype
Made new connections between new and old knowledge	Develop and implement engineering solution

2.1 PSS Micro-insertion

The PSS micro-insertion focused on enzyme kinetics with two specific aims: (1) create an active, constructive, and interactive learning space in a lecture-driven course, and (2) promote long term learning of the focused topic. To accomplish these goals, four class hours (50 mins each) were dedicated to PSS. The class of 24 students was divided into 6 groups (4 students each). Due to Covid-19 restrictions, students were grouped based on their regular seating chart to prevent disruption of daily contact tracing. All the students were juniors with no prior knowledge of enzyme kinetics. The PSS work was divided into 5 stages. (1) Mathematical derivation of the Michalis-Menton (MM) equation. The basics and steady-state assumptions for the equation were explained and applied during the first class. (2) Interactive brainstorming session to gather information about the real-world problem. (3) Analyze the data and learn the application of the MM equation. (4) Derive a new form of the MM equation (Lineweaver-Burk plot) as a group to analyze the data and make logical conclusions. (5) Reflect and summarize the learning by calculating maximum product formation rate (Vmax) and the MM constant (Km), relate it to the problem statement in an interactive online group discussion thread.

Stage 1 (Mathematical derivation): An active learning method of notes taking was utilized during the first class. The instructor went over the concepts of substrate-enzyme binding, the differential equations that dictated product formation rate, and steady-state assumptions to get to the MM equation. At this point, the instructor solved word problems for the control group (Fall 2020) on the board while students actively copied the problems. This method did not have any constructive or interactive learning. The control group did not experience any other stages discussed later in this section. However, the instructor did not solve any word problems on the board for the PSS group (Fall 2021), which allowed students to embrace the open-ended format of the next stages.

Stage 2 (Post-it Jamboard): The PSS activity started with rearranging the classroom such that the group members could work collectively on a single jumbo post-it. At this stage, students were only provided with the scenario of a *patient diagnosed with high cholesterol and on a prescription medicine- Lipitor. The doctor conducted a blood test to ensure the acceptance of the drug in his body after one week. After a few weeks, the patient started including grapefruit in his diet which impacted their health and liver. The doctor conducted another blood test to look at Lipitor metabolism in the body*. Students were allowed to discuss this scenario as a group, search for keywords, and write their questions and thoughts onto sticky notes they posted on their group's jumbo post-it. As seen from the student work (Fig 1A), each group added at least 10-15 questions on their jamboard.

Stage 3 (Data Analysis): During the third-class hour, students were given a worksheet where they constructed a hypothesis statement based on the sticky notes on their jamboard. In addition, students also had to think about '*what critical information would they need to run an engineering analysis to test their hypothesis*'. At least 4 groups independently created a statement close to the expected hypothesis of '*Lipitor metabolism is reduced after grapefruit consumption'*. Two groups needed discussion time with the instructor to lead them constructively towards this hypothesis. Based on the jamboard questions and their hypothesis statement, students projected that getting blood tests results conducted by the doctor before and after grapefruit consumption would help test the hypothesis. At this point, all the groups were given the blood test data set. Students immediately connected the data variables with the MM equation variables. Everyone used their laptops to analyze data on excel while two students shared a laptop. The characteristic plot (rate of product formation vs. substrate) for before and after grapefruit consumption tests showed distinct differences in the maximum rate of product formation. Students used their plots to discuss the engineering reason behind the doctor’s advice to their patient regarding discontinuing grapefruit.

Stage 4 (New Challenge): The last class hour was created to add a new challenge for the students. The Michaelis-Menton equation can be rearranged as a straight-line equation, called the Lineweaver-Burk (LB) equation. If data is mapped using the Lineweaver-Burk equation, variables such as Vmax and Km can be easily derived from the straight-line fit equation. The control group was never exposed to the LB equation as the MM equation was challenging for

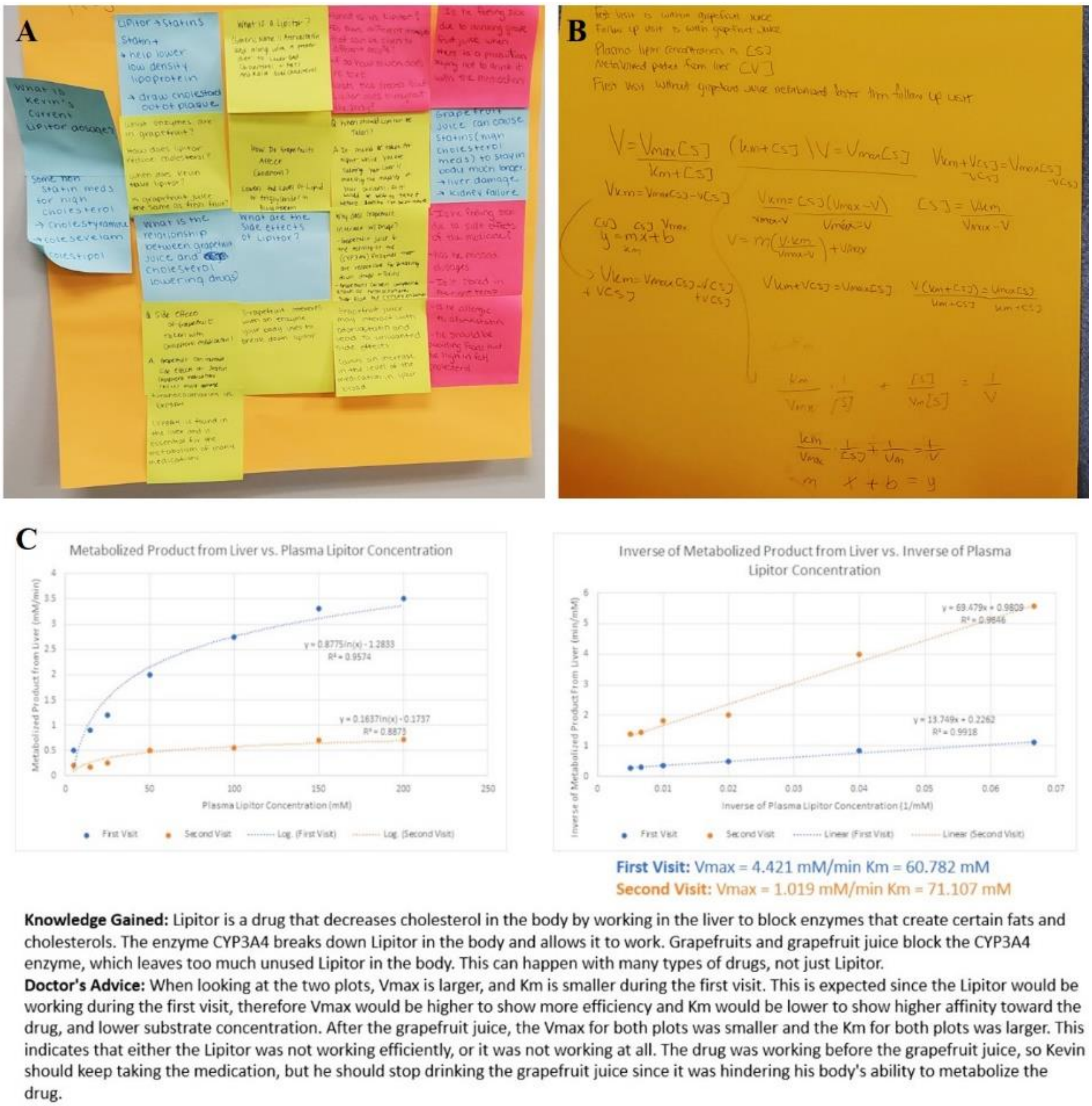

Figure 1: Student work from (A) jamboard showing questions written on post-its, (B) new challenge activity with The Lineweaver-Burk equation solution from the Michaelis-Menton equation and (C) one slide homework with reflection, graphs, and results analysis.

them. However, the PSS group was being introduced to this equation for the first time in the course during this activity. The instructor did not solve the LB equation on the board for the PSS group. Each group was given a prompt to rearrange the MM equation as a straight-line equation. All the groups worked on a new jumbo post-it together and constantly interacted with each other (Fig. 1B). Each group then re-plotted their data as a straight line and calculated Vmax and Km again for each blood test.

Homework (Online discussion board): Students posted a slide that included both plots they produced during the activity, data analysis, and their reflection on the discussion thread created on Kodiak (course dispensing tool). Besides, their group members were asked to comment on the slides and leave constructive feedback. Student work sample is given in Fig. 1C.

3. Results

The results for this study were summarized based on the technical questions, pre- and post-module survey, and teaching assistant observation.

Knowledge Assessment

The impact of the PSS module on student learning was assessed using a common question based on enzyme kinetics that was given to both the control and PSS group (Fig. 2A). As seen from the graph, the students who learned enzyme kinetics through PSS (average score of 65%) scored statistically significantly (Student's t-test, p-value=0.008) higher than the control group (average score of 48%). An additional comparison was conducted within the PSS group to test long term retention of technical knowledge. The students were given this question as a pop-quiz two days after the module ended. A question based on the same concept was given in the final exam that was conducted after 2 months of the PSS module. As seen in Fig. 2B, students scored an average grade of 79% in the pop-quiz and 69% in the exam with no statistical significance between the scores (p-value=0.3).

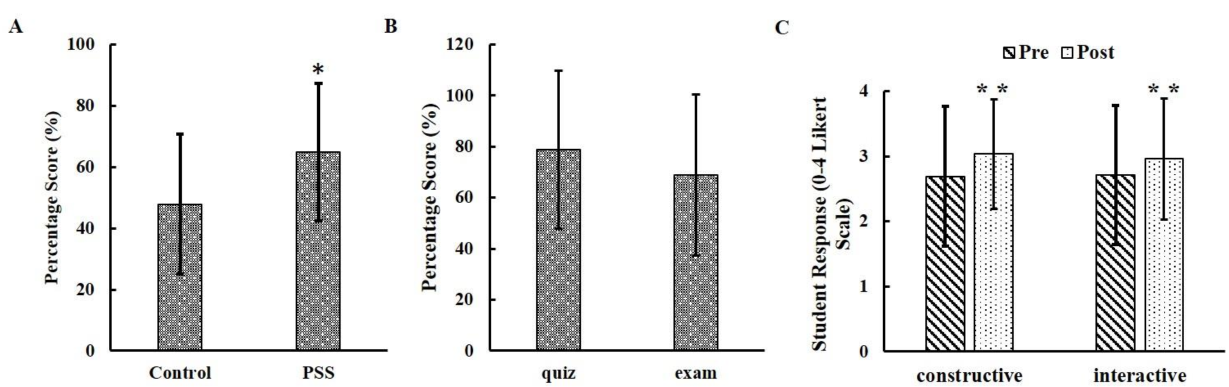

Figure 2: (A) Technical knowledge was assessed by giving the same question to PSS and control group showing significant improvement in test score (p-value<0.05). (B) Test scores of questions based on the Lineweaver-Burk equation asked 2 months apart as a quiz and final exam to PSS students were not significantly different, showing deep learning due to interactive PSS (p>0.05). (C) Constructive and interactive skills were significantly improved shown by pre- and post- PSS activity survey results (p<0.005).

Pre- and post-module survey
Pre- and post-module surveys were completed by 20 out of 24 PSS students. The questions assessed the impact of the PSS module on engineering mindset skills connected to constructive and interactive activities. There was a high internal consistency with questions related to each category with Cronbach's alpha of 0.87 and 0.84 for constructive and interactive category, respectively. Fig. 2C shows statistically significant (p-value=$1.4x10^{-6}$) improvement in engineering mindset related to constructive activities such as 'making connections between old and new knowledge', 'expands one's knowledge by gaining expertise', and 'evaluate technical feasibility of the mathematical model'. Similarly, skills associated with interactive activities such as 'communication with the group', 'effective incorporation of group and mentor feedback' and 'develop a novel model as a group that was not taught previously by the instructor' showed statistically significant improvement after the PSS module (p-value=0.0002).

Teaching assistant observation
The teaching assistant observed passive and active learning for the whole control group. Students took notes and listened to an intermittent explanation of the mathematical derivation of the MM equation. Almost 100% of the students were engaged in minimal active learning while copying the solution of the word problems from the board with no interaction with the professor or their peers. However, the degree of interaction among the PSS group was much higher throughout the activity as summarized in Table 3. During the jamboard session, students were engaged in active and constructive learning as soon as the problem statement was given. They searched for keywords or tried to understand what the problem was by asking relevant questions. After 10 mins, students became more interactive and discussed their findings with their peers and the instructor. The TA observed improved interactive learning throughout Day 3 compared to Day 2 during data analysis, especially during hypothesis construction and final result discussion. However, the use of laptops to generate graphs was categorized as constructive and active learning.
High energy interaction was observed among students during the 'new challenge' stage, even for the students who were normally disengaged. At least 2 groups got to the final answer within 20 mins of the class hour. Four groups needed initial help and discussion with the professor which made the process more interactive. Overall, the students who were not engaged were either on their cell phones or did not have a personal laptop for research or plotting the data.

4. Discussion
Mathematical modeling and associated word-problem-solving can sometimes fall under the category of troublesome knowledge. When a mathematical model representing a physiological system becomes difficult to understand, students try to memorize the method of solving a word problem. Since the ultimate goal set for a student is to get good grades, the emphasis shifts from learning the concept to finding a baseless ritual to get the correct final answer [9]. A similar situation was being observed during the enzyme kinetic section of the 'engineering physiology' class at WNE university. The objective of this work was to create a psychologically safe interactive environment based on the problem-solving studio structure [3]. Three-fold evaluation was conducted and technical knowledge was compared to the control group.

Technical Knowledge

As seen from Fig. 2, the hypothesis was accepted that the students who participated in PSS applied the Michaelis-Menton equation better than the control group. They were able to apply the knowledge in a stressful environment such as an exam and scored significantly higher than the control group. The knowledge gained during PSS had a deeper impact due to interactive activities compared to shallow compartmentalized knowledge gained during passive learning [10]. Figure 2B corroborates the long-term impact of PSS as there was no statistically significant difference in pop-quiz and final exam scores. Student comments also reflected better understanding of the equation: *"I learned the equation well and developed ideas",* and *"It was a good way to apply the class information".* In addition, PSS had a significant impact on student's analytical and data interpretation skills as seen from the reflection and online discussion homework. Students were able to give suggestions and constructive comments to their peers based on the knowledge gained during the class activity. Constructive peer comment such as *"I also liked how you included the name of the enzyme that is blocked by grapefruit juice, this is important in knowing what grapefruit juice affects in the body to prevent Lipitor from working and to assess what needs to be done after"* improves student learning and quality of work [11].

Interactive, Constructive, Active and Passive Learning

The PSS module was mainly designed to develop a highly interactive environment along with constructive learning. Figure 2C shows that the skills students developed during the PSS activity were scored significantly higher compared to the pre-PSS survey. Working in small groups, bouncing off ideas, constructive interaction with the professor, explanations of concepts, creating a hypothesis, making connection between class content and real-world problem enhanced cognitive learning [12,13]. Student response to what they liked in PSS also reflects that group interaction was the major factor in the learning process, *"Teamwork and communication", "team development",* and *"I liked working with a team and that it was interactive".* The detailed TA observation of the entire activity also gives insight regarding how different assignments created an interactive as well as a constructive environment. Chi et al. assumes fluid boundaries between the modes of the ICAP framework [6]. For example, the mathematical derivation of the MM equation was a combined active and passive learning experience. Even though students were actively writing, they were merely copying the content which resulted in minimal understanding and compartmentalization of the information to be reproduced in the same form. This shallow mode of learning resulted in low exam scores from the control group. On the other hand, all the activities in PSS shows that more than 60% students were either constructive, interactive or both at any time point. For example, post-it jamboard was a constructive and interactive activity. Students searched for new information, asked relevant questions, and connected new information to understand the problem statement. Towards the end, they discussed the new information and post-it questions within their group to co-create hypothesis for the next step. Initially, about 83.3% of the students were active while few were disengaged. This trend of initial disengagement could be attributed to resistance towards an unknown environment created by an open-ended problem [14]. Generally, students are habituated to following direct instructions in the form of copying solutions and memorizing them for exams. Once students overcome initial resistance and start exploring, they can engage in constructive learning. As seen from table 3, after 10-15 mins, all students were engaged in a cognitive method of learning. This was a trend seen during all three PSS stages where few students were disengaged initially but started communicating with their peers during the result discussion stage. This shows that the group dynamics inspired disengaged students to participate and learn [15]. Another reason for disengagement could be the use of laptops for data analysis which isolated the students and reduced communication. The TA observation regarding new challenge activity showed a progressive shift from 16.6% disengaged students to complete interaction.

Table 3: Time-dependent teaching assistant observations and percentage map of total number of students engaged in passive (P), active (A), constructive (C) and interactive (I) learning or not engaged (N-E) throughout PSS. The percentage distribution changes based on the nature of the activity and sub-activity.

<table>
<tr><th>Activity</th><th>Sub-activity</th><th>nth minute</th><th>I</th><th>C</th><th>A</th><th>P</th><th>N-E</th><th>Comments</th></tr>
<tr><td>Mathematical Derivation</td><td></td><td></td><td></td><td></td><td colspan="2">100</td><td></td><td>Students did not talk to each other and copied the content from board</td></tr>
<tr><td>Jamboard</td><td>Research keywords</td><td>10</td><td></td><td colspan="2">83.3</td><td></td><td>16.7</td><td>Students were quiet in the beginning and individually conducted research.</td></tr>
<tr><td></td><td>Discussion and creating sticky notes questions</td><td>25</td><td>41.6</td><td>50</td><td></td><td></td><td></td><td>• Students started talking with each other and discussed the reason behind the question on the sticky note.
• After 15mins of understanding the problem, they started asking questions from the instructor to get more information.</td></tr>
<tr><td>Data Analysis</td><td>Hypothesis writing</td><td>10</td><td>62.5</td><td>20.8</td><td></td><td>8.3</td><td>8.4</td><td>• Some students bounced ideas in their group.
• One group was disengaged as they were hesitant about creating hypothesis.
• Some members of the group were challenging the ideas of their group members.</td></tr>
<tr><td></td><td>Plotting data</td><td>20</td><td></td><td colspan="2">83.3</td><td></td><td>16.7</td><td>• Students worked on their laptops to plot the data.
• Some students were not interested in plotting the data.</td></tr>
<tr><td></td><td>Plotting data</td><td>30</td><td>75</td><td></td><td>8.3</td><td></td><td>16.7</td><td>• Students started interacting with each other and instructor to move forward.
• Some students were just copying the solution from their group members' work.</td></tr>
<tr><td></td><td>Result Discussion</td><td>50</td><td>91.6</td><td></td><td></td><td>8.6</td><td></td><td>• Disengaged students started talking with their group.
• Students were looking at their class notes to make connections.</td></tr>
<tr><td>New Challenge</td><td>Lineweaver Burk Equation</td><td>10</td><td colspan="2">83.3</td><td></td><td></td><td>16.6</td><td>• Leaderships started emerging, group discussions and collaborations were prominent.
• One group was disengaged.</td></tr>
<tr><td></td><td>Lineweaver Burk Equation</td><td>20</td><td colspan="2">91.6</td><td></td><td></td><td>8.6</td><td>• Groups were correcting their teammates work.
• Students were looking over their class notes to make connections.</td></tr>
<tr><td></td><td>Plotting data</td><td>30</td><td>50</td><td>50</td><td></td><td></td><td></td><td>Building off each other's work.</td></tr>
<tr><td></td><td>Calculation: Vmax, Km</td><td>40</td><td colspan="2">100</td><td></td><td></td><td></td><td>Groups encouraging each other's findings and adding on what they found.</td></tr>
<tr><td></td><td>Result interpretation</td><td>50</td><td colspan="2">100</td><td></td><td></td><td></td><td>Collaboration and discussion</td></tr>
</table>

During this activity, students communicated effectively and shared new ideas to create a new form of the mathematical model which was never taught to them. The TA observed that 'emergence of leaderships' and 'peer consultation' was maximized during the last stage leading to deep long-term learning as seen in Fig. 2B. Student comments specifically targeting the 'New Challenge' activity showed that increased communication and collaborative learning created a lasting impression on their perception of learning: *"I learned how to solve an equation and make it linear to compare values better"* and *"I learned the equation well and developed ideas"*.

Few limitations of this study include the impact of (1) utilization of two different TAs on control and PSS study, (2) face masks on TA observations, and (3) small sample size on overall results. TA observations were an important part of the ICAP class mapping. Even though both the TAs were trained by the same instructor to follow the same data recording method, this could be a potential source of error. The TA observations were also impacted by face masks used due to Covid-19 restrictions which limited TA's ability to observe conversation. The TAs relied on audible conversations and active physical interaction between group members. The last limitation is related to small sample size of the groups in this study. Since the average class size is 25-30 students in BME department, the problem of small sample size was mitigated by inclusion of a control study.

5. Conclusion

In conclusion, PSS was able to solve the troublesome knowledge related to enzyme kinetics and word problem-solving. Both the hypothesis statements were accepted due to the improvement in concept application skills after the PSS micro-insertion that enabled deeper learning. Rearranging the classroom physical space and working in small groups on common workstations directed towards real-world problems, enhanced the student outcomes. Even though students felt challenged initially, as a group they were able to overcome this hinderance and engage in a cognitive learning experience. The cognitive outcomes related to the ICAPS structure such as 'apply', 'transfer' and 'co-create' were achieved through series of interactive, constructive, and active techniques. In future, the group size will be reduced to two students as that will further promote active discussion. In addition, a classroom with desktop computers will be used to reduce the usage of personal laptops that created a disconnect within the groups during data analysis.

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