Application of Brain-based Learning Principles to Engineering Mechanics Education: Implementation and Preliminary Analysis of Connections Between Employed Strategies and Improved Student Engagement

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Application of cognitive-neuroscience learning principles to engineering mechanics education: preliminary analysis of connections between employed strategies and improved student engagement

Abstract

In a recent study, an instructional model that converts principles from cognitive neuroscience learning principles into instructional protocols has been developed and successfully yielded statistically significant learning outcomes in the Fluid Mechanics course in an HBCU. Motivated by that success, we extended a similar intervention to   the Dynamics course in the same department. In this *work in progress* paper, we report preliminary data from this intervention. The main strategies implemented in this intervention include the following: organization of the course into smaller-grain concepts and sub-concepts, which are concisely presented by short (limited to 2-6 minutes) content-rich lectures (diagrams and animations), active learning through in-class worksheets, and prompt feedback. The design of these instructional materials incorporated protocols derived from cognitive neuroscience, such as 'connect to relevant old/prior knowledge', 'creating of neural networks', and 'repeated use of neurons'. Results from this new implementation in the Dynamics course indicate that students' engagement and learning were significantly enhanced by this approach in a manner consistent with the Fluid Mechanics course. The data not only confirms the findings of our previous study but also suggests that the model's effectiveness may be independent of the developer and implementer of the model, if the instructional protocols are followed. Additionally, this study shed some light on the relative contribution of each of the strategies implemented towards the measured positive impact. According to student opinions, it was found that the greatest positive impact can be attributed, by far, to carefully designed in-class activities, followed by the quality of the lecture content.

Introduction and Background

A great deal of research has shown that engineering students who are more engaged in their class activities are more likely to succeed academically and professionally than those who are disengaged or distracted in class. There is ample evidence that the academic achievement of today's students falls below desired levels and that the lack of academic engagement is a major contributor [1, 2]. Devising effective solutions to the lack of engagement can be challenging, due the multiplicity and complexity of the factors affecting it. Such factors include student preparation, socioeconomic background and   teaching style effectiveness [3-5]. In this study, we extend our previous work that proposes a solution to this problem by specifically addressing two significant contributors to disengagement: the inadequate preparation of students for their courses and the traditional teaching style. Although our approach is conceived at and for an HBCU school students, it originates in cognitive neuroscience and the learning sciences and is applicable in any STEM field to any student population.

Research on teaching and learning has long suggested that the traditional approach to teaching, which faculty still commonly practice across the nation, could be a major factor contributing to the lack of engagement, motivation, and learning of today's students [6, 7]. The traditional

approach is generally marked by the instructor giving lectures and demonstrating the solution of example problems to students who (in theory) listen and take notes while occasionally asking questions for clarification. For student learning through practice, the instructor assigns weekly homework problems from a prescribed textbook which are like the ones whose solutions were demonstrated in class. Typically, students turn in their homework, which is then graded and returned within a week. This approach is acknowledged by researchers to be ineffective and incapable of engaging students collectively or individually, in part because it promotes both inherent student passivity during class and feedback delay, and it is incompatible with students' the learning styles, among others. All these aspects of traditional learning are at odds with findings of modern cognitive and behavioral learning research, which overwhelmingly agree that active learning is essential for any approach aiming at effective engagement and learning [8-11]. Researchers have developed different approaches to active learning including experiential learning [12], problem-based learning [13], case studies-based learning [14], and peer learning [15].

Another factor leading to disengagement of students in the upper level engineering courses is inadequate preparation. This issue is evident in deficiencies and/or misconceptions of pre-requisite concepts as well as foundational weakness in mathematical skills commonly cited by educators as essential for complex problem-solving. These weaknesses play an important role in student disengagement and ineffective learning in the upper level courses. The foundational deficiency and resulting disengagement can be particularly at play and self-perpetuating for students coming from underserved communities. An NSF-funded study performed at the mechanical engineering department at an HBCU school confirmed that foundational deficiency exists at upper level classes and this impedes engagement and their achievement of desired learning outcomes [16,17]. Mandating pre-requisite course has not been successful at preventing ill-prepared students from making their way to the upper level engineering courses. The study concluded that students who reach junior and senior level classes require a novel approach that is more systematic, engaging and tailored to the specific needs of individual students.

Using the principles of brain and learning sciences [18,19], Solomon et al. [16] proposed a novel instructional framework titled "Knowledge and Curriculum Integration Ecosystem" (KACIE) to improve student engagement and learning outcomes. The framework is based on a set of systematic cognitive neuroscience learning procedures (we call them protocols) to be followed during classroom interactions and in designing and delivering instructional materials. In this approach, the course is presented as a set of well-defined interconnected concise concepts and sub-concepts, which can be presented in about 5 minutes to leverage the typical focused attention span of a learner. Another important motivation for this concept-approach is the breakdown of complex topics into small manageable pieces, which in turn can be scaffolded to build larger understanding.

For the effective teaching of these concepts, the instructor should follow several protocols to guide the classroom interaction as well as to design the lecture content. Examples of such protocols include: P1 Connect to old/prior information, P2 Create neural connections, P3 Active learning component and P4 Repeated use of neurons. More details of the nine protocols appear in [16]. The framework does not require that all the protocols must be used in any particular

implementation. While it appears that the more protocols implemented the better, normally 4-6 protocols have proven sufficient for observable impact. The ultimate vision is for this framework is to extend beyond individual courses and to consider curriculum as a set of connected concepts and fundamental mathematical skills. Such a system may be useful for students to review and connect to concepts at higher levels more systematically and in a self-regulated manner. In a larger perspective, KACIE is designed to provide versatile framework for course structure, tools, and content, a framework into which fundamental principles from cognitive neuroscience learning can be implemented. These principles are the same as those that are the basis for other learning models, such as active learning, participatory teaching, and peer learning.

In this work, we extend the KACIE framework to the fundamental mechanics course Dynamics within the same department. Dynamics is a core mechanics course in departments like mechanical engineering and aerospace engineering. It covers the fundamentals of particle   and rigid body dynamics. Engineering students struggle with this course as it requires high level of analytical skills and strong foundation of basic physics concepts. Besides examining the effectiveness of the KACIE framework in a different course and setup, this work represents a step forward towards our goal of a systematic approach to connecting the whole curriculum by this framework. In spite of the different instructor (developer), implementation specifics, and course, the results from this first implementation of the KACIE framework in Dynamics indicate that student engagement and learning improved when compared to the control group taught using the traditional teaching, as described above. This provides additional evidence that teaching guided by cognitive neuroscience learning principles has the potential to improve student engagement and learning. It also shows that this framework is flexible and versatile. Finally, the questions of which and how many of the cognitive neuroscience learning principles to use to guarantee a positive outcome is a subject of further research.

Objectives and Research Questions

The goal of this research is to improve student engagement and learning by creating a systematic and flexible instructional framework which transcends individual courses to tie the whole curriculum as a set of interconnected concepts delivered through a hybrid face-to-face and virtual environment. The framework particularly targets the disengagement due to inadequate preparation (pre-requisite and math skills) and traditional teaching. Following the promising results of the pilot implementation in Fluid Mechanics, the objective of this work is to develop, implement, and test the effectiveness of KACIE framework in the course Dynamics. Due to the different conditions under which it is developed (still within the fundamental requirements of the framework), this implementation will consider a few aspects of KACIE framework originally designed for fluid mechanics course. To this end, we aim at answering the following research questions:

1. How transferable is the effectiveness of the KACIE framework in improving student engagement and learning influenced by the specific implementation setup (different developer, course, and   implementation specifics), i.e., is the KACIE framework flexible and effective in contexts other than the one in which it was originally developed?

2. Among the different elements of the KACIE, which are the most significant in improving engagement and learning?

Methods

Description of experimental intervention:

We start by describing the details of our specific implementation of the KACIE framework and its instructional protocols in Dynamics.

P1. Course presented as a set of well-defined and concise set of connected concepts/sub-concepts: By design, the concept description is small-grained and limited so that that it can be reasonably presented within a focused attention span of about 6 minutes. If the concept does not fit this criterion, then it is appropriately divided into sub-concepts to meet the criterion. Breaking the course in this manner has been expected to result in better engagement and scaffolding.

P2. Lecture slides to accompany the presentation of each concept: The slides are prepared in accordance to the following pattern. At the beginning of the new concept presentation, the slides revisit the foundational knowledge and concepts needed to understand the new concept (protocol P1 above). Besides setting the proper stage to deliver the new concept, this approach helps uncover misconceptions which might exist. Following that, the concept is presented along with examples to create new neural connections (protocol P2). The chosen examples draw on practical situations that students have a feeling for and to which they can connect. Although such situations are imaginary, they provide more engaging learning experience (protocol P3). Finally, the slides were prepared with animations. This strategy is more effective in keeping students' attention, which would improve engagement and aid learning process.

P3. In-class problem-sets accompany the concept presentation: Students complete problems within the class period or within a specified time. The problems are designed to be short and targeting a specific aspect or skill related to the concept. Such in-class activities provide an opportunity for students to strengthen new neural connections developed in relation to the presented concept (protocol P4). In contrary to the passivity of students in the traditional approach to teaching, this in-class activity allows the students to engage actively in the learning process, which is expected to result in better learning outcomes [9]. Additionally, students are given the option to work individually or collaboratively in accordance to their preferences.

P4. Prompt feedback: It is well-known that a main requirement for effective learning is continuous and prompt feedback [20]. This feature is inherent to the KACIE framework by the in-class KACIE worksheet where student can get prompt feedback on their solutions to problems and the opportunity to fix their solutions.

The following four course topics and their related concepts were selected for this implementation:

projectile motion, path coordinate system (normal/tangential component), relative motion, and particle kinetics using Newton's Second Law.

Participants in experimental intervention:

There were 33 students who participated in this study in Fall 2017. Dynamics is a 3-credit hour required course in both the mechanical and the aerospace engineering curricula and covers kinematics and kinetics of particles and rigid bodies. This sophomore level course is observed to be challenging as it demands analytical skills and sufficient foundational background in basic physics and mathematics.

Experimental design and procedure:

To determine the impact of the KACIE intervention described above, the experimental group was compared to a control group. The control group consisted of students at the same school who have taken the same course offered in a traditional manner from the same instructor from 2015-2017. Although assessing the equivalence of the previous and treatment cohort can be involved a check for homogeneity suggests relative equivalence of the groups. Since our treatment did not start till about the third week of the semester during which the teaching style was traditional, we compared the performance of the treatment and previous cohorts based on same or similar standard examination problems in both groups, including the treatment group before beginning the treatment. We found that the average score for the two groups were 46.7 and 47.5 percent with a p-value of .85, which indicates an appropriate parity for plausible comparison. Subsequent studies will employ more in-depth homogeneity assessment and options for controlling for any differences.

The assessment of the impact of the intervention consisted of two elements. First, the performance of the two groups on the same or similar examination problems graded by the same instructor was compared. The comparison was performed on the overall performance on all the topics (see *Description of experimental intervention* above). For additional insight the concept-based performance was also compared. Second, anonymous student opinion surveys were performed to gain insight on the impact of the intervention. The survey solicited overall feelings of students about the impact of this approach on their learning and engagement as well as the relative impact of the four elements of the intervention described above. Among the 27 students (out of the 33 participants of the experimental group) who chose to complete the survey, 7 students happened to be retaking the course in both format (traditional and KACIE) by the same instructor. With the same samples in place, this cohort provides a unique opportunity to gain further insight into the impact of the intervention.

Results and Discussion

Performance on calculation-based problems:

Fig. 1 compares the overall (over the four topics included in the experiment) average percentage score of the control and experimental groups. As seen from the figure, the experimental (KACIE) group average was 10 points higher than that of the control group (59 compared to 49 percent).

To verify that this difference is a reliable, the t-test was performed assuming two-tailed distribution with unequal variance samples. The p-value was found to be 0.002 which is less than the typical alpha threshold of 0.05 indicating that the difference is reflective of the impact of the KACIE intervention. For additional insight the averages for each individual topic were compared in the same figure. With a difference of 26 and 18 percentage points for the path coordinates and Newton's 2nd Law, respectively, along with a p-value of less than 0.05, it is evident that the KACIE approach has positive impact on students' learning as measured by their performance on typical examination problem. As for the relative motion and projectile motion topics, the averages indicate that the KACIE did not result in any improvement. For the case of the relative motion, the explanation for this unexpected result might be the deficient vector and vector algebra foundation of the participating students. This deficiency was evident to the instructor during classroom interactions and acknowledged by the students. Solving calculation-based problems in relative motion requires strong background in vector algebra. It is worth noting that this background deficiency is a good example of the issues that originally motivated the KACIE instructional approach [16, 17]. This deficiency can be addressed by providing precise concept-based materials prepared following implementation of the KACIE framework protocols.
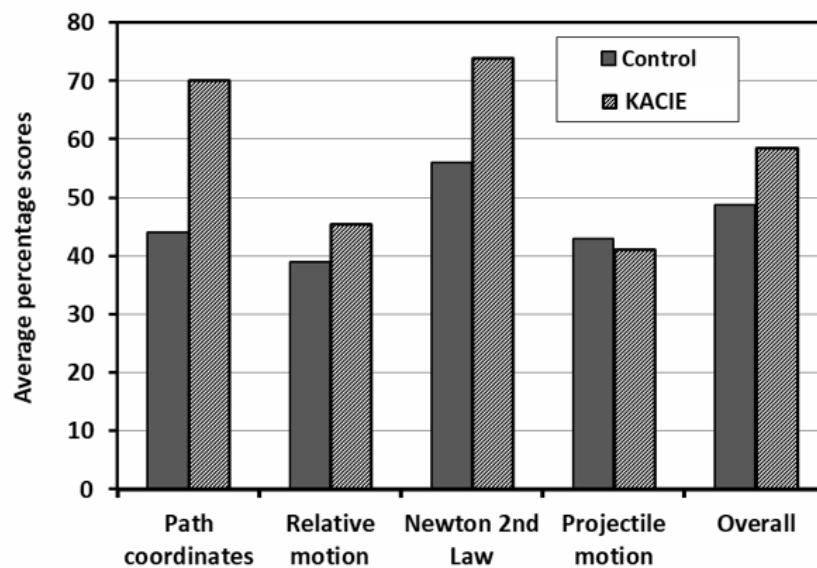
Fig. 1 Comparison of control and experimental (KACIE intervention) groups' overall and specific performance on calculation-based problems in different topics in Dynamics.

Student opinion survey:

For additional insight based on the personal experience of students with the KACIE system, an anonymous survey of student opinions was conducted. The survey consisted of three sections. Table 1 shows the results of the first part of the survey which directly solicited students' feeling about their engagement and learning levels. The first column shows the statement to which the student must respond with a number on a scale of 5 representing the extent to which the student agreed with the statement as follows: 1) strongly disagree, 2) disagree, 3) neutral, 4) agree and 5) strongly agree. As can be seen from the table, the students' experience is positive on the different

counts of engagement and learning. 56% of students agreed (22% strongly so) that the approach was more engaging during class meeting time and 41% agreed that the engagement extended beyond the class time. Although the improved engagement can be mainly attributed to the in-class worksheet activities, it can also plausibly be attributed to the other elements of KACIE such as improved lecture design and delivery methods which are informed by cognitive neuroscience learning principles, the breakdown of the course topics into small-well defined concepts, and the prompt feedback. The same can be said about the learning experience of students. 59% of the students thought that the approach helped them better understand the course concepts and 67% of the students agreed that KACIE provided a systematic approach which is more conducive for their learning. The percentage of students who, overall, felt that their learning experience was improved was 56%. Those results are in general agreement with the results obtained from comparing students' performance on exam-style calculation-based problems.

Table 1, Percentage of students at different levels of agreement with the statements made. The scale is 5 with 1) strongly disagree, 2) disagree, 3) neutral, 4) agree and 5) strongly agree

Statement	1	2	3	4	5
I found that this KACIE implementation is more engaging during class than the traditional approach	3.7%	18.5%	22.2%	33.3%	22.2%
I found that this KACIE implementation is more engaging outside class than the traditional approach	7.4%	11.1%	40.7%	29.6%	11.1%
I feel that this KACIE implementation helped me better understand the course concepts	3.7%	3.7%	33.3%	51.9%	7.4%
I feel that this KACIE implementation provided a more systematic approach that is more conducive for learning	3.7%	7.4%	22.2%	51.9%	14.8%
Overall, I learn better if the KACIE approach is used	7.4%	3.7%	33.3%	44.4%	11.1%

As mentioned above, an interesting cohort of seven students who took the same course from the same instructor in both formats (traditional and KACIE) occurred. This group is unique in the sense that the human factor is more effectively neutralized on both the student and instructor ends. When asked to respond by "yes" or "no" to how they agree the following two statements: "*KACIE was more engaging*" and "*I learned the material better with KACIE*" the percent of students who answered "yes" was 85.7%. This suggests additional confirmation of the findings of this pilot implementation of KACIE in Dynamics.

As mentioned above, one of the designs or aspirations of the KACIE system is that it should be transferable and flexible if its protocols are followed in the instructional process. This study suggests that even a limited implementation of KACIE is effective. To understand this, a preliminary investigation into the impact of four elements of the KACIE system was performed through a student survey instrument. Table 2 shows the results of how students ranked the impact of only four elements of KACIE structure which were implemented in this study. For example, the table shows that 21.1% of the students ranked Element 1: "presenting the material as a collection of concepts" as the element of highest contribution to the positive impact of KACIE. As the table shows, 47% thought that, among the different elements of the approach, the in-class worksheet was the most significant contributor to the improved engagement and learning while 32% though it was the content (slides) made available to them. By the time the time the

second element is significance is added, 70% of students though the in- class work sheet is the element which made the difference as opposed to 54% who thought it was the content. In fact when asked about the level of importance of the content, 70% thought the provided content was very important and 26% thought it was important for their learning. Those preliminary results are interesting and call for more research as they can allow instructors to get the most impact of their effort when implementing all nine of the protocols may not be practical or possible.

Table 2, Percentage of students attributing the positive impact of the KACIE intervention to its respective elements: First is the most significant and Fourth is the least.

Element of KACIE implementation	Significance			
	First	Second	Third	Fourth
presenting the material as a collection of concepts	21.1%	11.1%	25.0%	66.7%
in-class worksheets	47.4%	27.8%	16.7%	11.1%
prompt feedback	0.0%	38.9%	33.3%	11.1%
concept lecture slides which follow brain-based learning protocols	31.6%	22.2%	25.0%	11.1%

Limitations and Assumptions

Two important limitations merit note. First, the study assumed the relative homogeneity of the groups with respect to background skills and preparation. In the next iteration of the study, background skills and preparation will be controlled. Second, any time an instructional innovation is implemented, there is a novelty effect that may skew results positively or negatively. While that limitation is acknowledged, it is important to assess results from the implementation as a baseline for initial claims and further research.

Conclusion and Future Work

A framework for instruction, KACIE, which is based on the cognitive neuroscience learning principles was developed and tested in the core mechanics course Dynamics. The implementation consisted of four elements (strategies) which are motivated by four cognitive learning protocols. Finding of this study can be summarized as follows:
- Despite the different conditions under which KACIE was implemented, it proved to be effective in improving students' engagement and learning.
- The results of this work provide evidence of the transferability and versatility of KACIE because it is founded on brain and learning sciences
- The results show that KACIE can be effective even if not all the nine protocols are implemented. This finding is a motivation for further research to determine which protocols (or combinations of) are most effective to implement when limitation and constraints do not allow the ideal implementation of all nine protocols
- Based on student opinions, in-class problem-sets and lecture design based on cognitive learning protocols were the two most significant elements (strategies) of the current

KIACE implementation to which the improvement in engagement and learning are attributed

For future work, the equivalence between the control and experimental cohorts with regard to their preparation level, engagement level, and prerequisite mathematical skills should be established so that measured student learning gains are adjusted accordingly. To avoid instructor subjectivity and bias, the assessment methods of student performance should be standardized including in the way the performance levels are measured. Finally, the same methodology needs to be tested by other instructor in different setup to ensure the validity and transferability of the treatment.

Acknowledgement:

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