Visualization Aids for Abstract Concepts Towards Better Learning Outcomes

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***Abstract*— The engineering disciplines of industrial engineering, engineering management, and systems engineering are replete with abstract concepts without physical representations that are inherently difficult to learn. Hence, this study is motivated by engineering students' inability to understand abstract concepts and the need for continuous improvement of student learning. In this study, in the context of supply chain decisions making that is economically rational, we show how we constructed and analyzed an evidence-based, in-class example of visualization aids that help engineering students to develop better understanding of abstract concepts needed in engineering problem solving. Specifically, our example was implemented in a junior level undergraduate production systems course in an industrial engineering program, which covers the areas of supply chains and logistics. To see if the visualization aids that are designed to complement the traditional approach of mathematical derivations and numerical computations, we utilize a randomized-controlled design research framework implementing the visualization aids in a quiz. Namely, an intervention group of randomly selected students were always provided with visualization aids accompanying each problem whereas a control group of randomly selected students were not. Students' quiz results from both groups were statistically compared, and the statistical analyses of results show that, within the scope of the aforementioned experiment and collected data, the visualization aids help students understand abstract concepts better. The insights obtained throughout this study from the design of the visualization aids to the implementation of them in an in-class quiz will be presented. Such insights will serve as guidelines for future educational research on visualization aids towards better student learning outcomes of abstract concepts.**

Keywords—Abstract Concepts; Visualization aids; Learning Outcomes

I. INTRODUCTION

Various engineering disciplines ranging from industrial engineering to systems engineering and engineering management all rely on abstract concepts without direct physical representations. For example, supply chains, enterprise computing, or complex engineering projects – to name a few.

A significant challenge exists in teaching and learning of such abstract concepts as frequently observed sequence of events in classrooms shown below.

1. Abstract concepts often expressed as concise mathematical models, and are quantitatively derived in class.
2. Such models are mathematically solved for solutions often using optimization techniques, differential equations, or equilibrium methods.
3. Students demonstrate their abilities to arrive at such solutions not only analytically, but also numerically or computationally often using algorithms.
4. Once the desired solutions are obtained, a significant number of students are at a loss to explain what they have as solutions, their relationships to key parameter values of the mathematical models, and the ramifications often involving managerial insights as well as economic implications.

We observe that quite a few of our students work hard to derive the correct solutions analytically, numerically, and/or computationally. And then we further observe that such students do not understand the solutions that they have correctly obtained as in #4 above.

As documented in the next section (Literature Review), under these circumstances, we find the potential of visualization aids promising, and we ask the following engineering education research question:

Can visualization aids help students understand abstract concepts without physical representations often found in the engineering disciplines of industrial engineering, systems engineering, and engineering management? If yes, to what extent?

In this paper, towards addressing this research question, in the context of supply chain decisions making that is economically rational, we show how we construct and analyze an evidence-based, in-class example of visualization aids that help engineering students to develop better understanding of abstract concepts needed in engineering problem solving.

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Specifically, we show how a short module of economic decision making in supply chains is implemented in a junior level undergraduate production systems course in an industrial engineering program, Then, to study if and to what extent visualization aids help students understand abstract concepts without physical representations, complementing the traditional approach of mathematical derivations and manipulations, we utilize a randomized-controlled design research framework and implement the visualization aids in a quiz.

For this quiz, an intervention group of randomly selected students are always provided with visualization aids accompanying each problem whereas a control group of randomly selected students are not. Students' quiz results from both groups are then statistically compared, and the statistical analyses of results show that, within the scope of the aforementioned experiment and collected data, the evidence shows that the visualization aids help students understand abstract concepts better.

The rest of the paper is organized as follows. First we present a review of relevant literature. This is followed by the description of the methodology used for this experimental study. Next, we show how the resulting quiz performance is statistically analyzed, and present our research findings. Finally, we make concluding remarks and comment on future research.

II. LITERATURE REVIEW

Using various images and animations for teaching and learning mathematics has been frequently reported for its many potential benefits (see e.g., Zimmerman and Cunningham 1991). For example, Tall (1991) found that, when students drew graphs that represented physical shapes such as slopes or areas, they developed a better understanding of calculus.

As for engineering education, there also are many examples of visualization tools to aid student learning. For example, Heath et al. (1995) suggested that the visual display of performance data on parallel computing was important for student comprehension. Extensive research has demonstrated the efficacy of visual aids on students learning across a variety of domains, including learning verbal materials, spatial layout, sports rules, mechanical structures, etc. (see e.g., Novick et al. 1999).

As for why it may work, a promising reason that visual models improve student understanding is that visual cues help learners offload part of the conceptual processing required to the visuospatial domain, thus freeing up valuable verbal resources in working memory (Haugwitz et al. 2010).

Due to its effectiveness in promoting learning, mathematical educators have advocated increased use of visual aids in the classroom (Barwise and Etchemendy 1991), but visualization aids for abstract concepts in engineering have not been as widely adopted. In industrial engineering, systems engineering, and engineering management domains (which all share common interests in supply chains), the impact of visualization on learning abstract concepts has not been studied.

III. METHODOLOGY

As mentioned in Introduction and Objectives Section, our aim is to study the impact on student learning of visualization aids. For this purpose, first, the basic subject areas on supply contracts for technology-oriented critical materials of high volatility were introduced in IE 341, Production Systems. IE 341 is an upper division Industrial Engineering (IE) course that is required for all BSIE majors. We note that these areas are inherently concerned with supply chain lead time and time value of money under uncertainties over price and demand over time.

Next, students studied managerial insights and economic implications based on mathematical models and analyses via a series of lectures in class. In addition, a short manuscript accompanying the series of lectures (called Project Contents) was provided to each student. For both the lectures and the manuscript, no visualization aids were provided. Afterwards, the aforementioned study for the impact on student learning of visualization aids was conducted with the following procedures and participants, as well as the test contents as below.

Procedures and Subjects

Students in the class were randomly divided 2 groups, C (Control) and I (Intervention). In Group C, 41 students participated in the test while in Group I, 39 students participated in the test. Most of the students were industrial engineering students at the junior level and senior level.

Prior to the test, the purpose of the study was explained to the students according to IRB approved procedures and students had the option of signing a consent form to participate in the study. Students were informed of their group (C or I) assignment, and they were assigned a test location based on their group. All students were given 30 minutes to complete the test. Upon completion, tests were graded and the results were evaluated using an adjusted confidence interval recommended by Agresti and Caffo (2000).

Notation

n_C Number of subjects in the control group

n_I Number of subjects in the intervention group

X_C Number of correct answers for the control group

X_I Number of correct answers for the intervention group

$\tilde{p}_C$ Adjusted sample proportion for the control group

$\tilde{p}_I$ Adjusted sample proportion for the intervention group

The estimate of the mean proportion, p, is the adjusted sample proportion which is given by

$$\tilde{p} = \frac{X+1}{n+2}$$

and the sample standard deviation is defined as

$$S = \sqrt{\frac{\tilde{p}(1-\tilde{p}}{n+3}}.$$

The confidence interval for the difference between the adjusted sample proportions for groups C and I is given by

$$(\tilde{p}_I - \tilde{p}_C) \pm z_{\alpha/2}\sqrt{s_I^2 + s_A^2}\ .$$

We expected the use of visual aids for group I would result in a positive difference in the proportion of students who found the correct answer. If there is a statistically significant difference between the groups, then the confidence interval should not include 0.

Test Contents

The test consists of 3 questions. Each question is asked as a multiple choice format, and each student is asked choose one answer among 4 choices. The first 2 questions are concerned with the economic decisions for supply chain members focusing on lead time aspects, and both groups C and I are provided with corresponding visualization aids. For the third question, only group I is provided with visualization aids.

For the sake of concreteness and specificity, we present the actual questions as follows.

No. 1 Assuming that all the other parameter values remain the same, let us now suppose that the parameter value of *L* has increased. Is this good news to the intermediary company? Recall that higher P^* implies that the intermediate company is less likely to do business with the local supplier. Please circle your answer (i.e., directly circle (a), (b), (c), or (d) below).

(a) Yes if $0 < L < \hat{L}$ and $\hat{L} > 0$.

(b) Yes if $0 < L$ and $\hat{L} < 0$.

(c) Yes if $\hat{L} < L$ and $\hat{L} > 0$.

(d) Yes if $\hat{L} = 0$.

For your visualization aid, the following two figures are provided.

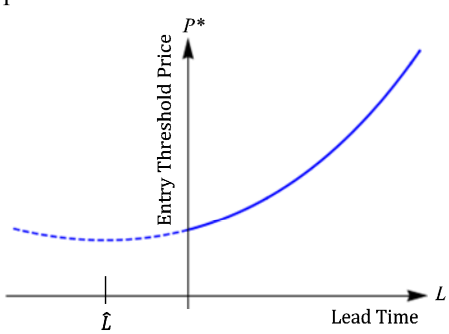

Figure 1. P^* vs. L when $\hat{L}$ is negative

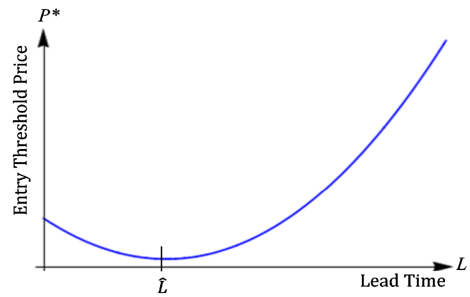

Figure 2. P^* vs. L when $\hat{L}$ is positive

No. 2 Which of the following statements is true? Recall that higher P^* implies that the intermediate company is less likely to do business with the local supplier, and assume that all the other parameter values not mentioned in the statements remain the same. Please circle your answer (i.e., directly circle (a), (b), (c), or (d) below)

(a) If P^* decreases, under no circumstances, L could have increased.

(b) If P^* decreases, under no circumstances, L could have decreased.

(c) If P^* increases, under some circumstances, L could have stayed the same.

(d) If P^* increases, under some circumstances, L could have decreased.

Note: two figures identical to Figure 1 and Figure 2 in Question 1 were provided for the student's use during the quiz.

No 3. Please recall the cost and revenue stated on Page 10 of the Project Contents document. Which of the following statement is true? Assume that all the other parameter values not mentioned in the statements remain the same. Please circle your answer (i.e., directly circle (a), (b), (c), or (d) below).

(a) When L is (relatively) large, the revenue defined in the Project Contents document will be discounted more heavily compared to when L is (relatively) small.

(b) When L is (relatively) large, the cost defined in the Project Contents document will be discounted more heavily compared to when L is (relatively) small.

(c) When L is (relatively) small, the revenue defined in the Project Contents document will be discounted more heavily compared to the cost defined in the Project Contents document.

(d) When L is (relatively) small, the revenue defined in the Project Contents document will be discounted less heavily compared to the cost defined in the Project Contents document.

For your visualization aid, the following figure is provided.

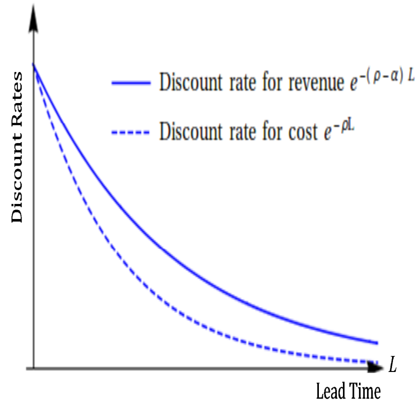

Figure 3. The shapes of discount rates over lead

As mentioned earlier, only group I was provided with this figure (i.e., group C was not provided with this figure). We note this problem specifically tests students' understanding that the cost is discounted more substantially when the lead time is relatively short while the revenue is discounted more substantially when the lead time is relatively long.

IV. RESULTS

The results of our analysis are shown in Table 1 for each of the questions. The difference for question 1 was not significant. However, a significant difference was observed for both questions 2 and 3. We expected that there would be no difference for questions 1 and 2 because both groups were presented with the same descriptions and visualization aids for those questions.

Table 1 Confidence Intervals for the differences between groups.

	Q1	Q2	Q3
$\tilde{p}_I$	0.73	0.68	0.54
$\tilde{p}_C$	0.65	0.47	0.30
$\tilde{p}_I - \tilde{p}_C$	0.08	0.22	0.23
S	0.099	0.104	0.104
Lower CI	-0.089	0.042	0.069
Upper CI	0.250	0.394	0.400

One possible explanation for these results could be a disparity in the reasoning ability of each group. As shown in Figure 2, group I consistently outperforms group C, which may explain the difference for question 2. However the gap increases significantly for question 3, suggesting that there was an additional factor influencing the result, in this case the visualization aid. It should also be noted that the difficulty of the questions based on the scores was Q3>Q2>Q1. Given the sharp drop in scores for question 3 for both groups, additional visualization aids may be warranted for lecture content.

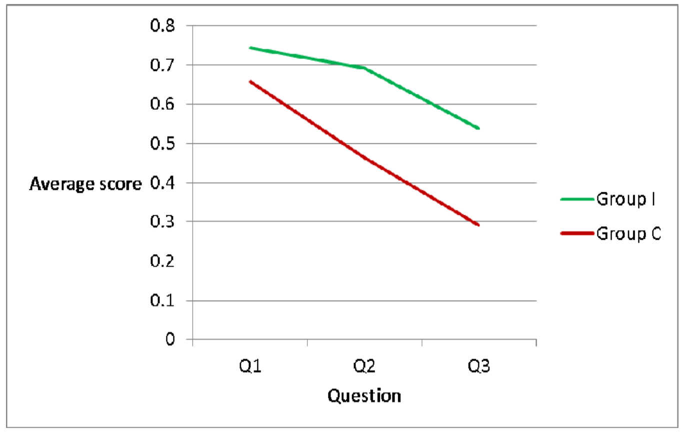

Figure 4 Average scores for each group

V. CONCLUDING REMARKS AND FUTURE RESEARCH

In this paper, our research questions are: Can visualization aids help students understand abstract concepts without physical representations often found in the engineering disciplines of industrial engineering, systems engineering, and engineering management? If yes, to what extent?

Towards addressing these questions, we constructed and analyzed an evidence-based practice case in the context of the economic decision making on supply chains using a randomized-controlled design research framework and visualization aids in a quiz.

The statistical results indicate that visualization aids help students understand the abstract concepts without physical representations. Also, the insights gained from the Results section will serve as guidelines for future educational research on visualization aids towards better student learning outcomes of abstract concepts. We do note that, however, our exploration in this paper is an initial step as the scope and scale of this research must substantially expand to fully address the proposed research questions. For example, more tests may lead to better quantification of the magnitude of student learning improvement via visualization aids by increasing the confidence level of the results.

As for future research, in addition to the expansion of scope and scale, one could further investigate mental representation models to explain why students' understanding improved with visualization aids. For example, are these visualization aids enable students to relieve some of the requirements imposed on short-term memory for engineering problem solving (in the direction of the aforementioned literature in Literature Review Section)? Separately, one could further investigate, in addition to visualization aids, if and to what extent tactile aids help students understand abstract concepts (for example, tangible forms of various shapes representing the integration of inventory mass over time).

Finally, we note that although this study focused on abstract concepts in industrial engineering, systems engineering, and engineering management, the research findings can be extended to other related areas of engineering, other STEM's, business, management, and economics.

In addition, there are now numerous cross-disciplinary areas such as leadership and entrepreneurship for engineers that would be able to utilize visualization aids for abstract concepts for teaching and learning.

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