AC 2011-1767: THE EFFECTS OF WORKED EXAMPLES ON CAD PERFORMANCE: AN APPLICATION OF THE FOUR-COMPONENT INSTRUCTIONAL DESIGN MODEL TO CAD INSTRUCTION

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The Effects of Worked Examples on CAD Performance: An Application of the Four-Component Instructional Design Model to CAD Instruction

Abstract

This presentation discusses enhancements to current instructional practices for engineering graphics and constraint-based modeling courses taught at the collegiate level, and introduces a novel application of an instructional design framework, 4C/ID, directed towards the design and dissemination of interactive CAD tutorials. Several engineering graphics researchers and instructors have made efforts to accommodate the challenges of blended instruction by designing general CAD tutorials that attempt to leverage embedded video resources. However, the literature reports few cases of systematic design and evaluation of instructional strategies based on cognitive learning theory. In this study, a total of 161 students enrolled in GC120-Foundations of Engineering Graphics were divided between control and experimental treatments, with the experimental group receiving tutorial videos designed around the 4C/ID model. These two groups were analyzed for the ways in which the tutorial videos were used to support learning solid modeling tasks and how this knowledge was subsequently transferred to novel solid modeling tasks. Data were analyzed in order to determine the best practices for creating and administering CAD tutorials in hybrid learning environments. Considerations for furthering the authors' line of inquiry into constraint-based modeling instruction are addressed as well.

Introduction

Within the area of Computer-Aided Design (CAD) education there has been dissent regarding the efficacy of some of the instructional methodologies employed to teach students (trainees) solid modeling and other CAD processes (e.g., rapid prototyping). Some educators and practitioners have suggested that CAD education is inadequately preparing students for procuring gainful entry-level employment in the workforce because graduates do not have the skills that are necessary for meeting the fluctuating demands of the engineering and manufacturing industries[1, 2.] Ye, Pong, Chen, and Cai[3] surveyed over 150 CAD professionals holding a variety of roles in the manufacturing and engineering industries (e.g., CAD users, application and software developers, and managers) about what skills and training were necessary for trainees to possess upon entry into the workforce. A majority of the responses of the CAD professionals indicated that students should be able to effectively use CAD to solve engineering problems. Likewise, Ault and Giolas[4] found similar results when they conducted investigations into industry trends relative to CAD practices. The crux of CAD and its execution relies on constraint-based solid modeling (i.e., solid modeling) as a means of producing a visualization or representation of 3D components or parts of an assembly and simulating the functionality of those parts, and most studies that have explored the state of CAD and solid modeling relative to academia and industry have found that one key competency that needs to be addressed in solid modeling instruction is *design intent* [5-7].

Design intent is the intelligence or sophistication integrated into an engineered part during the solid modeling process[8] and it governs how a part and the relationships between its features behave when subjected to the iterative modifications characteristic of the design processes used by many engineering firms and manufacturers[9]. Choi, Mun, and Han[10] defined it as "a set of geometric and functional rules which the final product [has] to satisfy" (p. 14). For example, if a part requires alterations after being reviewed by an engineer, that part's features should update in a predictable fashion relative to its construction history, parameters, and constraints. These can take the form of either geometric changes or topological changes, where the former refers to alterations in the size or shape of a model's features and the latter pertains to the creation or removal of feature elements (i.e., edges or faces)[11]. In the context of a solid modeling software package, a geometric change might include altering the diameter of a hole after the feature associated with parameter has been created while a topological change would be deleting a feature all together. While design intent is inundated with complexity, it does form the foundation of a student's skill sets and competencies, and plays a central role in CAD education[6].

Rossignac[12] contended that the inadequacy of CAD education and solid modeling instruction resulted not from a disparity between industry trends and academic curricula but that it was attributable to "the discrepancy between the elegant formulations promoted in scientific publications and the intuitive, often much simpler, mental models that are helpful when probing the validity of a solution, looking for counter examples, or inventing proofs" (p. 1461). While beyond the scope of this paper, a mental model is an internal representation which one acts upon in order to execute an action[13, 14]. If this mental model is informed by fallacious information then acting upon it will produce erroneous behaviors, whereas if it is robust it can result in efficient CAD practices (e.g., the appropriate use of solid modeling strategies)[15, 16]. During solid modeling instruction *elegant formulations*, solid modeling examples and problems that only display the application of solid modeling strategies in a limited context, are often employed. Unfortunately, they do not necessarily promote students' abilities to formulate design and engineering problems, or use solid modeling to solve these problems; they actually inhibit students' performance on solid modeling tasks. Many engineering graphics textbooks that discuss solid modeling have elegant formulations, they display solid modeling problems that appear to have one predetermined solution and require a regimented course of action to be completed when, in actuality, there may be many modeling strategies for solving such solid modeling problems that vary in applicability and efficiency[5].

Piegel[17] asserted that example-based learning has the potential to counteract the effects of elegant formulations and possibly enhance CAD education and solid modeling instruction. He stated that "people can learn much faster by seeing examples, that is, CAD design tools can be enhanced by design-by-example methods" (p. 466). A worked example is a prototype of expert problem solving processes, and it models these processes as well as a problem formulation, solution steps and strategies, and a final solution to the problem[18, 19]. Worked examples can be designed so they fully explicate the solution of a problem or partially delineate the procedure by requiring the trainee to complete the problem independently in varying contexts[20]. It is these qualities that differentiate worked examples from elegant formulations—worked examples are intended to guide one through a problem solving process, whereas elegant formulations are decorative at best and do not necessarily facilitate learning. In the context of solid modeling instruction, a web-based tutorial video that includes a narrator demonstrating a solid modeling strategy is an example of a worked example[21].

This paper seeks to examine how worked examples can be incorporated into an instructional regimen for solid modeling instruction in an undergraduate engineering graphics course and how this instructional regimen affects performance on solid modeling exercises designed to assess learners' ability to generalize solid modeling strategies. In particular, this paper focuses on how example-based solid modeling instruction administered using the Four-Component Instructional Design (4C/ID) model can impact students' ability to perform solid modeling tasks. Instruction in 4C/ID is compromised of four components: whole-task practice (i.e., learning tasks), part-task practice, supportive information, and just-in-time information[24]. Whole-task practice occurs within task classes where each task class contains several learning tasks arranged from simple to complex. During whole-task practice, learners perform tasks that require them to apply and execute a skill in real and simulated conditions (e.g., a pilot in training may use a flight simulator to learn how to operate an aircraft). Whole-task practice also includes demonstrations and guidance intended to help the learners get acclimated to the task (termed supportive information). Supportive information helps enhance these skills and can come in the form of worked examples. As whole-task practice proceeds, the assistance (i.e., supportive information) provided to the learner gradually fades, so that the learner can perform the entire skill without any guidance. Part-task practice is separate from whole-task practice and focuses on developing the automaticity of the procedural aspects of the task under consideration. Just-in-time (JIT) information comes in the form of rules, step-by-step directions, and feedback and it can be presented during whole-task practice and part-task practice. In the 4C/ID model, whole-task practice occurs first, with part-task practice occurring subsequently. The whole-task practice includes supportive information and JIT information, and the part-task practice only includes JIT information. This workflow proceeds until all of the learning tasks in the task class are completed[24].

One of the goals of 4C/ID is transfer of learning, the generalization and extension of skills from one problem situation to another[25]. Transfer of learning is concerned with "how previous learning influences current and future learning, and how past or current learning is applied to similar or novel situations" [26] (p. 23). Haskell[26] suggested that near transfer happens when knowledge acquired from one situation is applied to a new, yet similar, situation while far transfer refers to the application of previous knowledge to a new situation that is markedly different from the situation where the knowledge was acquired. According to Sternberg[27] positive transfer and negative transfer refer to relative difficulty under which transfer takes place; he suggested that positive transfer "occurs when the solution of an earlier problem makes it easier to solve a new problem" (p. 581) whereas with negative transfer occurs when solving a new problem on the basis of prior knowledge is difficult. The 4C/ID model facilitates positive near and far transfer of learning by the combination of whole-task practice and part-task practice. The whole-task practice requires a trainee to create and apply multiple mental models of a task while part-task practice develops the efficiency necessary to execute the procedural components of a task.

Despite the discord that exists regarding the sufficiency of current CAD education the literature offers certain alternatives for enhancing the efficacy of CAD education and solid modeling instruction – example-based learning is capable of helping trainees create robust mental models of solid modeling strategies and the 4C/ID model is a conduit through which example-based learning can integrated into solid modeling instruction. An application of the 4C/ID model to the solid modeling instruction in a section of an undergraduate engineering graphics course should produce substantive differences in learning outcomes when compared to another section of the same engineering graphics course that has not received solid modeling instruction structured according to the 4C/ID model. During exposure to such an intervention, learners in the section receiving the 4C/ID intervention should experience a similar amount of near transfer to a control section on solid modeling tasks, but also should observe a higher amount of far transfer than their counterparts on novel solid modeling tasks. In the following section the instructional invention used to make this comparison will be described in detail.

Methods

A total of 161 undergraduate engineering students enrolled in two sections of an introductory engineering graphics course participated in this study. The majority of the participants were aerospace, civil, and mechanical engineering majors and either held sophomore or junior standing at the university. The age range of the participants was between 19 and 21 years.

This study utilized worked examples in the form of multimedia tutorial videos demonstrating solid modeling (SM) strategies that were structured according to the 4C/ID model and delivered via the course's multimedia learning management system (LMS). Each engineering graphics lesson in the course included a SM component to which the videos pertained. The tutorial videos were designed in several formats based upon the instructional components of the 4C/ID model (e.g., whole-task practice and part-task practice). Whole-task videos (full videos) emphasized a solid modeling strategy and displayed an expert engaged in problem solving, modeling a part from start to finish. Part-task videos (partial videos) included those that solely presented the procedural aspects of a particular modeling process (e.g., a task may involve multiple extrusions and it is necessary that the process of creating an extrusion becomes intuitive to the learner) and design intent videos presented and demonstrated brief SM activities that reinforced the process of embedding intelligence and functionality into a model. *Assessments* were used to evaluate participants' knowledge of the SM content presented during the solid modeling instruction delivered in this study. Each assessment consisted of five questions randomly presented to participants in true-false, multiple choice, or fill-in-the-blank formats. Each question was worth 10 points, up to a maximum of 50 points per assessment. There were also two SM exercises that coincided with each lesson and evaluated the amount of near transfer and far transfer experienced by the participants. These exercises are referred to as *near transfer SM exercises* and *far transfer SM exercises*, respectively. Both types of SM exercises were scored out of 100 points according to predetermined evaluation criteria.

Two experimental conditions were present within this study: 1) a treatment condition (n=60) that received access to one full video, one partial video, and one design intent video per lesson, and 2) a control condition (n=61) that only received access to one full video per lesson. This study took place over the course of two lessons in an engineering graphics course where one lesson took place per week. The data for this paper came from a much broader research study that explored example-based learning for solid modeling instruction and the mental models of design intent that CAD trainees produce while engaging in solid modeling tasks. Each section of the engineering graphics course was randomly assigned to either the treatment condition or the control condition. During each of the two lessons, participants in both conditions completed an assessment and then were required to view the videos corresponding to their respective experimental conditions. After viewing the videos for a lesson the participants were then required to complete a near transfer SM exercise and a far transfer exercise that coincided with that particular lesson. At the end of the study participants completed a final assessment.

Results

It is evident that the participants in the treatment condition scored higher on each assessment than the control condition's participants, but not significantly so as indicated by a 2 x 3 mixed ANOVA (see Table 1). Their assessment scores were only slightly greater than their counterparts' and this was also the case with regard to their near transfer SM exercise and far transfer SM exercise scores within each lesson, neither condition significantly differed from the other regarding these scores (see Table 2). In contrast, the control condition achieved a better performance on the Lesson 2 far transfer SM exercise than the treatment condition. Spearman's Rank Correlation indicated that, generally, performance on the Lesson 1 near transfer SM exercise and the far transfer SM exercise were significantly related, r_s=.283, p<.05; and that a significant association existed between participants' performance on the Lesson 2 near transfer and far transfer SM exercises, r_s =.515, p<.01. Upon further inspection it was apparent that these associations were predicated upon the performance of the participants in the control condition because in both Lessons 1 and 2 their near transfer SM exercise and far transfer SM exercise scores were related, r_s =.419, p<.05, and r_s =.501, p<.05, respectively.

An analysis of the transfer of learning experienced by the participants was performed using the one of the transfer of learning formulae proposed by Gagné, Foster, and Crowley[28] that permits an examination of the amount of positive and negative transfer experienced by learners completing multiple tasks. The formula used during this analysis takes into account the aggregate scores of the treatment condition and control condition on each of the near transfer and far transfer SM exercises and analyzes the extent of positive or negative transfer of learning that has occurred as a result of a treatment or intervention by "giving direct expression to [the] amount and direction of transfer" [28] (p.

4) in the form of a percentage (see Figure 1). For the near transfer SM exercise associated with Lesson 1, 31.24% transfer was achieved and -24.77% transfer was observed with the lesson's far transfer SM exercise. Whereas the SM exercises pertaining to Lesson 2 both displayed positive transfer with the near transfer SM exercise exhibiting 36.16% transfer and the far transfer SM exercise exhibiting 18.27% transfer.

Table 1: Assessment scores

	Assessment 1		Assessment 2	
Condition	M	SD	M	SD
Treatment	45.63	8.73	42.26	8.24
Control	44.21	6.42	42.22	8.76

Table 2: SM exercise scores

	Treatment				Control			
	Near Transfer		Far Transfer		Near Transfer		Far Transfer	
	M	SD	M	SD	M	SD	M	SD
Lesson 1	85.36	14.52	73.10	21.83	78.71	20.77	78.44	26.26
Lesson 2	78.57	25.49	78.75	26.43	66.43	33.59	74.00	26.96

Note: In this table near SM exercises and far SM exercises are referred to as near transfer and far transfer, respectively.

Figure 1: Transfer formula

$$\text{Transfer} = \frac{\text{Treatment Group Score} - \text{Control Group Score}}{\text{Total Possible Score} - \text{Control Group Score}} \text{ X } 100$$

Discussion and Recommendations

The participants in the treatment condition outperformed those in the control condition on all of the assessments by a slight yet nonsignificant margin and, similarly, the treatment condition achieved a scant amount of improvement on the near transfer and far transfer SM exercises relative to the control condition. The Lesson 1 far transfer SM exercise scores were an exception to this trend because the control condition exhibited better performance on the exercise than the treatment condition. The authors asserted that participants in both experimental conditions were likely to experience a similar amount of near transfer on solid modeling tasks and that a greater amount of far transfer would be observed in the treatment condition but although the data did not confirm these assertions, the underlying agency by which the results were achieved does deserve examination.

An exploration of the type and amount of transfer resulting from the treatment yields some interesting *outcomes* relative to the efficacy of the instructional intervention. It is apparent that due to the instructional intervention, the treatment condition could readily apply the skills that they had acquired during the lessons to solid modeling problems requiring that those skills and modeling strategies be utilized similar to the ways that they had been demonstrated in the tutorial videos. For example, the treatment participants experienced 31.24% positive transfer during the Lesson 1 near transfer SM exercise and 36.16% during the Lesson 2 near transfer SM exercise. The quantity and direction on the Lesson 1 and Lesson 2 far transfer SM exercises varied as demonstrated by the amount of negative transfer, -24.77%, that occurred with the Lesson 1 far transfer SM exercise; a minimal amount of positive transfer (18.27%) was exhibited with the Lesson 2 far transfer SM exercise. As far transfer of learning requires the generalization of learned skills to markedly novel problems, the negative transfer occurring with Lesson 1 indicates that the treatment inhibited the participants from extending and applying their knowledge acquired from the lesson to a new or atypical solid modeling problem and deriving a solution[26]. Since the positive transfer observed with the Lesson 2 far transfer SM exercise was minimal at best it is likely that this amount of transfer was challenging to achieve and that the treatment was only somewhat assistive to the participants.
The results found in this study could have been caused by several factors including the content of the tutorial videos and the types of parts that the participants had to model during the near transfer and far transfer SM exercises. The solid modeling strategies demonstrated in the tutorial videos for Lesson 1 emphasized the creation of elementary sketches and the modeling of parts primarily containing one feature. The near transfer SM exercise reflected this whereas the far transfer SM exercise required a small amount of design intent in the form of sketch relations to be employed. Lesson 2 introduced modeling strategies that employed more sketches and more features, and the near transfer and far transfer SM exercises coincided with that content. The treatment condition also viewed a part-task video and a design intent video corresponding to each lesson's content. The biggest difference between the lessons was that Lesson 2 introduced and emphasized a significant amount of design intent for sketches and features whereas Lesson 1 did not.

If an instructional regimen similar to the treatment presented in this study was to be employed in another engineering graphics course, certain considerations would have to be made. First, such an instructional regimen needs to be utilized for more than two lessons – the 4C/ID model specifies that it is most effective when applied over multiple lessons[25]. It is possible that students need to become acclimated to the use of worked example videos and understand how to effectively use them in learning. Students might well have been cognitively overloaded in initially learning the solid modeling software, and the additional overhead of the worked examples initially exerted a negative effect—especially on the more difficult far transfer problem. For that reason, tutorial videos that explicate solid modeling strategies should be structured such that a full modeling strategy is demonstrated, a partial modeling strategy requiring the learners to complete a modeling process independently is demonstrated, and a demonstration of how design intent functions and can be applied to a particular part is delineated. Lastly, learners should be required to complete several near transfer and far transfer SM exercises that coincide with the tutorial videos. This will allow them to develop the robust mental models necessary to engage in near and far transfer of learning.

The results of this study contribute to several lines of inquiry present within engineering education research such effective solid modeling instructional practices and online instruction for CAD education. Although this study demonstrates that solid modeling instruction structured according the 4C/ID model has the potential to increase the efficacy of instruction by addressing the fallacies of *elegant formulations,* the way(s) in which the 4C/ID model can be applied in CAD education needs to be further explored. The size of the sample and the time span in which the study was executed limited the generalizability of the findings presented in this paper. What was not addressed in this study was the type and quality of mental models necessary to produce superior near transfer and far transfer on solid modeling tasks. Future research should explore manipulations of solid instruction according to different instructional design frameworks because such explorations will enable the adequacy of CAD education and solid modeling instruction to be enhanced.

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