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Evaluation of a meta-tutor for constructing models of dynamic systems

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ABSTRACT

Modelling is an important skill to acquire, but it is not an easy one for students to learn. Existing instructional technology has had limited success in teaching modelling. We have applied a recently developed technology, meta-tutoring, to address the important problem of teaching model construction. More specifically, we have developed and evaluated a system that has two parts, a tutor and a meta-tutor. The tutor is a simple step-based tutoring system that can give correct/incorrect feedback on student's steps and can demonstrate steps for students when asked. Because deep modelling requires difficult analyses of the quantitative relationships in a given system, we expected, and found, that students tended to avoid deep modelling by abusing the tutor's help. In order to increase the frequency of deep modelling, we added a meta-tutor that coached students to follow a learning strategy that decomposed the overall modelling problem into a series of "atomic" modelling problems. We conducted three experiments to test the effectiveness of the meta-tutor. The results indicate that students who studied with meta-tutor did indeed engage in more deep modelling practices. However, when the meta-tutor and tutor were turned off, students tended to revert to shallow modelling. Thus, the next stage of the research is to add an affective agent that will try to persuade students to persist in using the taught strategies even when the meta-tutoring and tutoring have ceased.

1. Introduction

This paper reports progress on two research problems: (1) teaching students how to construct mathematical models of dynamic systems, and (2) teaching students to use effective learning strategies. Both research problems have long histories, which are covered in the next few sections.

1.1. A brief history of educational uses of system dynamics modelling

There are two distinct reasons why students should learn model construction. First, modelling is an important cognitive skill in itself. The Common Core State Standards for Mathematics (CCSSO, 2011) considers modelling to be one of 7 essential mathematical practices that should be taught at all grade levels. The Next Gen standards for science instruction (National, 2012) also have 7 strands that are threaded throughout the standards, and modelling is one of them.

Second, modelling is widely believed to be an important method for learning domain knowledge. For instance, modelling has been claimed to help in achieving a deep understanding of scientific systems, economic systems and other systems (Chin et al., 2010; Metcalf, Krajcik, & Soloway, 2000; Stratford, 1997), removing misconceptions and making of conceptual changes (Booth Sweeney & Sterman, 2000; Bredeweg & Forbus, 2003; Hestenes, 2007; Lee, Jonassen, & Teo, 2011; Mandinach & Cline, 1994b; Wilensky, 2003; Wilensky &

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Reisman, 2006), understanding the epistemology of models in science (Treagust, Chittleborough, & Mamiala, 2002), and developing intuitions, predilections and skills at understanding complex phenomena in general (Hogan & Thomas, 2001; Mandinach & Cline, 1994a; Schecker, 1993; Steed, 1992).

In short, modelling is both an important cognitive skill and a potentially powerful means of learning many topics. That is, it is both an end goal and a means to other end goals.

The modelling activity addressed here is traditionally called *system dynamics* modelling (see Collins and Ferguson (1993) for a particularly comprehensive taxonomy of modelling). The model is comprised of real-valued variables that are constrained by temporal differential equations. The variables denote quantities in the system whose values change over time. The job of the model is to predict those changing values as accurately as parsimony allows.

There is a long history of using system dynamics model construction as in instructional activity. According to the oral history of the System Dynamics Society (http://www.systemdynamics.org/oral-history/), system dynamics began to be used for university instruction around 1957 with Jay Forrester's formulation of system dynamics for teaching management. When a graphical language, Stella, became available (Richmond, 1985), instructional usage dramatically increased and extended to high school. Many early Stella projects trained teachers in modelling and let them invent activities (Mandinach & Cline, 1994a; Zaraza & Fisher, 1997).

After years of experience by hundreds of teachers, observers began to report that getting students to actually construct models took so much class time that most teachers used Stella only for model exploration activities, wherein students were given a model and were asked to observe how graphs of the variables values changed as the students manipulated parameters of the model (Alessi, 2000; Doerr, 1996; Mandinach & Cline, 1994b; Stratford, 1997).

Laboratory studies confirmed the observers' reports about both the length of time required for model construction and the importance of model construction. For example, Hashem and Mioduser (2011) found that students who *constructed* NetLogo models learned more about emergence, self-organization and other complex system concepts than students who *explored* NetLogo models that were given to them. The comparison took place during two 90-min lessons on complex systems, which were flanked by a pre-test and a post-test. However, prior to the pre-test, it took only 2 h to train the model exploration group whereas it took 48 h to train the model construction group. In a review of the modelling literature, VanLehn (2013) found that the only experiments that produced reliable positive results for model construction also devoted at least 5 h to training the students before the main lessons.

This history motivates the specific research problem addressed here: How can we speed up students' acquisition of skill in constructing system dynamics models?

Many methods for accelerating the acquisition of skill in model construction have been implemented, but only a few have been compared to baseline versions of the model construction activity in order to test their effectiveness (see VanLehn, 2013, for a review). Of those that have been evaluated, one form of scaffolding has shown considerable promise: The use of feedback and hints on student's steps in constructing the model. A whole model is usually composed of many parts (e.g., nodes, links, equations, labels, icons, numbers, etc.) which the student enters one at a time. Entering such a part is called a "step". Systems that give feedback and hints on steps are called *step-based tutoring systems* (VanLehn, 2006). Step-based tutoring systems have been used for a wide variety of tasks besides model construction, and appear to be almost as effective as human tutors (VanLehn et al., 2011). Thus, this project decided early on to build a step-based tutoring system for system dynamics modelling in the hope that it would accelerate students' acquisition of modelling skill.

1.2. Learning strategies research

A learning strategy is a process, procedure or method that meets two criteria (Donker, de Boer, Kostons, Dignath van Ewijk, & van der Werf, 2014): (1) Students can use the strategy when studying, but it is not required by the material that they are studying. (2) Using the learning strategy is believed to affect the student's learning. A good learning strategy is thought to improve students' learning, while a poor learning strategy is thought to harm the students' learning. When used without modification, "learning strategy" generally means a good learning strategy. Some examples are:

- When memorizing facts, a good learning strategy is to construct a mental image and associate each fact with a part of the image.
- When studying an example, a good learning strategy (called self-explanation) is to explain each step in the example to yourself, asking "Why is this true? Why did the author include this step?"
- When reading a text, a good learning strategy is to reflect afterwards on what you have learned.
- When reading a text, a poor learning strategy is to ignore words or passages that you don't understand.

Learning strategies have been studied for decades, and comprehensive meta-analytic reviews exist (Donker et al., 2014; Hattie, Biggs, & Purdie, 1996). Some of the main findings are:

A. Students often exhibit poor learning strategies.
B. Good learning strategies can be taught, often with little difficulty.
C. When students use the taught learning strategies, their domain learning often increases compared to students who are not taught to use the learning strategies.
D. When instruction in the learning strategy includes meta-cognitive and motivational components, students can often be prevented from reverting to poor learning strategies when the instruction ceases.
E. Specific learning strategies often have larger effect sizes than general purpose ones.

These findings mean that research on learning strategies is intimately linked to advances in instruction. Whenever a new instructional method or subject matter is developed, there are likely to be poor learning strategies that are specific to it (finding A) as well as specific good learning strategies that are likely to be effective (finding E) and easily taught (B). The key question is whether they are effective for