Using Teachable Agent Feedback to Support Effective Learning-by-Teaching

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Abstract
Teachable agents build upon research showing that students can learn by teaching their peers. In these systems, students learn by teaching simulated pupils who can be designed to support productive types of feedback and teacher-pupil interactions. We found that students learned better when they taught an agent designed to mimic a self-regulated learner (i.e. pushed the teacher to ask questions, and probe the agent for explanations to check her understanding). Analyses of log file data showed that interacting with the agent helped students engage in beneficial learning and teaching behaviors.

Keywords: teachable agents; log file analysis; learning-by-teaching; metacognition; self-regulated learning; feedback

Introduction
Teachable agents are computer-based environments designed to support learning-by-teaching in middle school classrooms (Biswas, Leelawong, Schwartz, Vye, & the TAG-V, 2005). The students do not instruct an actual peer, but instead teach a simulated pupil that accepts input from the teacher and uses that information to answer questions. These agents do not simulate the full range of actions available to a human pupil. They may also not engender the same commitment to “good teaching” that a human pupil would; the stakes are not as high. On the other hand, the simulated pupils are consistent in their interactions with their student teachers, and they can be designed to emulate good student behavior. Our design of teachable agents is usefully informed by research on learning-by-teaching in human teaching settings (Bargh & Schul, 1980; Roscoe & Chi, 2007). One focus of our research has been on how students learn by teaching and to look for ways to manipulate interactions with the teachable agent to enhance the learning process.

Previous research on learning-by-teaching has established that teaching a peer offers meaningful learning opportunities for the teachers, which emerge directly from the teaching process (Roscoe & Chi, 2007). The process of explaining, asking questions, and evaluating pupil feedback may help student teachers engage in reflective knowledge-building. Teaching a peer can help students evaluate their own understanding, and then refine and revise their knowledge. As a result, the teachers’ knowledge can become more complete, correct, and coherent.

For example, explaining key principles may help peer teachers evaluate and perhaps reorganize their own knowledge (Coleman, Brown, & Rivkin, 1997). The teacher must first articulate their knowledge, which helps to make main ideas more explicit. These verbalized ideas may then be more accessible to metacognitive evaluation and refinement. Interactions between the teacher and pupil are also a vital aspect of this process (Roscoe & Chi, in press).

Teachers are not explaining the material for their own benefit; the explanations need to be understandable and educational for their audience. This may require teachers to attend to the errors of their pupil, and further revise their explanations or generate new explanations.

Additional support for knowledge-building stems from pupils’ questions (Graesser & Person, 1994; Roscoe & Chi, 2007). Pupils’ questions can introduce ideas that the teachers omitted or new ideas for discussion. Pupils’ questions might also offer unintended metacognitive cues that the teachers’ knowledge is incomplete or flawed. Pupils might ask questions because the teachers’ explanations do not make sense and need to be reconsidered and improved.

The impact of pupils’ actions and questions on the teacher can be characterized as a form of feedback (Schwartz, Blair, Biswas, Leelawong, & Davis, in press). A teachers’ general goal is to get the pupil to understand the concepts and related problems, and so the pupils’ actual or apparent understanding provides indirect feedback on how well the teacher is doing. In regards to learning-by-teaching, the pupils’ performance is partly a reflection or product of the teachers’ domain knowledge and strategies.

From this perspective, two major stumbling blocks for learning-by-teaching and knowledge-building arise. One problem is that many students are not very good at gauging their own comprehension (Azevedo & Cromley, 2004). They may falsely judge that they understand when they do not, or fail to detect contradictions between their beliefs and other sources of information. Because learning-by-teaching requires a significant degree of self-monitoring and self-regulation, student teachers may not always appreciate or utilize pupil feedback effectively. This may be especially true for middle school students, who tend to have low prior domain knowledge and little teaching experience.

Another obstacle could be inconsistent or poor quality feedback from the pupil. Human pupils may also monitor their own learning ineffectively. Thus, when peer teachers ask “Do you get it?” a response like “Yeah, I think so” could be very misleading. Another nontrivial problem is pupil passivity. In teaching and tutoring situations, some pupils do not say much and ask few questions (Graesser & Person, 1994), thus providing very little feedback to the
teacher. Pupils also possess their own prior knowledge and misconceptions. Some pupil errors will not actually be indicative of any problem on the part of the peer teacher.

These issues suggest that teachable agents need to be designed in ways that simultaneously support self-regulation for the student teachers, and limit problems of inaccurate or irrelevant agent feedback. We also wish to avoid agents that employ their own strategies or possess prior knowledge of the material, which can confuse or frustrate the student teacher (Leelawong & Biswas, in press). The agents should also be designed to respond to the student teacher in an active, consistent manner that accurately reflects what the agent “knows,” and is thus more reflective of the teachers’ performance. We hypothesize that feedback of this nature will support more effective learning-by-teaching with teachable agents, even for middle school students.

We have developed a teachable agent system called Betty’s Brain in which students teach an agent about river ecosystems. In this paper, we describe a study that manipulated the kinds of metacognitive feedback that the system provided to the students. Student learning was assessed based on student-generated concept maps and written pretest/posttest measures. We also analyzed log file data (i.e. records of students’ interactions with the system) to test whether the variations feedback influenced the students’ learning and teaching behaviors.

Betty’s Brain

Teaching Betty

The teaching process in Betty’s Brain is organized around three activities: teach, query, and quiz (Biswas et al., 2005). Throughout this process, students can also access text resources that provide information on river ecosystems.

To teach Betty, students generate a representation called a concept map (Novak, 1998) consisting of concepts and causal relationships. Students can teach Betty concepts such as “fish” and “carbon dioxide,” and relationships such as “fish exhale carbon dioxide.” Students also indicate whether the first entity causes an increase or decrease in the second; when fish exhale carbon dioxide, carbon dioxide increases.

Independent of learning-by-teaching, this process of editing their concept map could also help students to better understand the material (Nesbit & Adesope, 2006; Novak, 1998). Similar to explaining, concept mapping requires students to externalize their knowledge. This may facilitate self-evaluation (e.g. checking whether links make sense) and knowledge revision (e.g. modifying the concepts).

Furthermore, the visual representation of the concept map structure (Figures 1 and 2) makes chains of reasoning more explicit. For example, a map may indicate that “fish eat macroinvertebrates, and macroinvertebrates eat algae.” This representation may help students realize the implicit idea that fish indirectly affect the amount of algae.

The query function allows students to ask Betty causal questions about entities in the river. These questions are generated using a pull-down menu. Students specify two entities and a change in the first entity. An example might be “If carbon dioxide increases, what happens to algae?”

Betty uses qualitative reasoning methods to follow all of the chains of concepts and links connecting the two concepts. Betty initially answers questions by giving the output of her reasoning process, such as “I think if carbon dioxide increases, algae increases.” These answers can be correct or incorrect depending on the correctness or completeness of what she has been taught. In addition, students can request Betty to explain her answer. Betty will begin to articulate the paths she followed to produce her answer. In order to get Betty to explain her entire reasoning process, the student teacher may have to ask her to continue her explanation several times.

The quiz function allows student teachers to have Betty take a quiz consisting of pre-defined questions. After taking the quiz, Betty’s answers are graded by a mentor agent, Mr. Davis. Grading is done by comparing the answer produced by the students’ map to the answer produced by an underlying expert map that has all of the required concepts and links. Thus, students know which questions Betty answered correctly or incorrectly and what her answer was for each. Mr. Davis also provides additional feedback after Betty takes a quiz.

Feedback from Betty

The basic version of the system enables some of the features of desirable pupil feedback that we argued should support learning-by-teaching. When asked a question, Betty will always try to answer, and will always justify her answer (based on the concept map she has been taught) if probed. Thus, passivity is less of a problem. In addition, Betty only knows what she is taught about the domain; she has no prior knowledge or preconceptions. This means that her knowledge and mistakes are almost always relevant to the students’ own knowledge and errors.

For this project, we extended another version of the system in which Betty provided more active and
Participants and Conditions

This version employs a self-regulated learning (SRL) framework. Self-regulated learning describes a set of comprehensive skills such as setting learning goals, selecting appropriate strategies, and monitoring one’s learning progress and strategies (Azevedo & Cromley, 2004). Betty’s SRL persona incorporates aspects of this metacognitive knowledge (Wagster, Tan, Wu, Biswas, & Schwartz, 2007). For example, as students add concepts and links, Betty sometimes spontaneously re-explains what she has taught. This is similar to how self-regulated pupils might restate and draw further inferences from what a teacher has said in order to make sure they understand it.

The SRL version of the system does more than just produce spontaneous statements from Betty. We have identified patterns of teacher actions where metacognitive feedback might be useful. For example, sometimes students ask Betty to take the quiz but have not taught her anything new since the last quiz, or probed her understanding with a question. Betty “knows” that she is probably not ready and will actually refuse to take the quiz. The response given to the student would be “Are you sure I understand what you taught me? Please ask me some questions to make sure I got it right.” The students cannot progress with the quiz unless they teach her more or ask a question.

However, asking lots of queries is not sufficient either. If students do not occasionally ask Betty to explain her reasoning, she will ask the teacher to do so; “You have not asked me for my explanations lately. Please make me explain my answers to you know if I really understand.” Thus, Betty strongly urges her student teacher to probe the complex chains of reasoning in the map more deeply. In this case, students are able to continue their teaching without requesting an explanation if they so choose.

In essence, SRL Betty captures teacher-pupil interactions where the pupil is active and aware of when she may not be learning. Her feedback further encourages the teachers to evaluate Betty’s knowledge (i.e. their own knowledge) and make revisions when necessary. Our prediction is that this enhanced, SRL-inspired form of teachable agent feedback will improve learning-by-teaching outcomes.

Method

Participants and Conditions

Our participants were 56 students in two 5th grade science classrooms, taught by the same teacher. The study took place in a relatively high-achieving public middle school during the 2005-2006 school year.

Students were assigned to one of three conditions using stratified random assignment based on standardized test scores. Students in the learning-by-teaching (LBT, n = 17) condition taught Betty using the basic version of the system. Students in the self-regulated learning (SRL, n = 19) condition taught Betty using the SRL version. In the intelligent coaching system (ICS, n = 18) condition, students created maps for themselves and did not teach Betty, but these students could still use all teaching, quiz, and query features. System responses were delivered by Mr. Davis, the mentor agent. They did not receive SRL feedback.

These manipulations occurred during the main phase of the study (seven 45-min. sessions). After an eight-week delay, students participated in a transfer phase (five 45-min. sessions) in which they learned about the nitrogen cycle and taught Betty using an identical version of the LBT system.

For this paper, we only focus on data from the main phase.

Learning Assessments

Student learning was assessed through two measures. One measure was the final map generated by students at the end of the main phase. These maps were coded to identify correct inclusions of concepts and links based on the text resources provided. The number of correct concepts and links was tabulated to produce an overall map score. This measure is an indicator of how well students could model the network of causal relationships that explain the functioning of a normal river ecosystem.

A second measure was a written assessment testing students’ understanding of underlying principles and processes. This test included eight free response and ten multiple-choice questions, which covered concepts such as interdependence, balance, photosynthesis, and food chains. Each free response question was worth six points to allow students to earn partial credit. Each multiple choice question was worth one point. We included this measure because the text resources discussed these principles related to the river ecosystem. By reading the resources to teach Betty, students might also acquire this conceptual knowledge. However, although understanding these ideas would help students teach Betty better, the current system does not require students to teach Betty this kind of information explicitly.

Log File Analyses

As students interact with the system, log files are generated that record each action. Such actions can be captured in five basic categories: editing the map (EM), accessing the text resources (RA), asking a query (AQ), requesting a quiz (RQ), and asking Betty to explain her reasoning (EX).

Editing the map (EM) is the most basic activity students could engage in. This is how students input their domain knowledge to create the maps. Map editing can be done...
simply by shallowly reading the resources (RA) and then putting the facts into their map. Quizzing (RQ) and querying (AQ) are potentially more metacognitive in nature. These actions allow students to evaluate how well their map represents the information. One advantage of queries is that they target a specific relationship between two concepts. In addition, students must actively formulate the query themselves (as opposed to relying on pre-defined quiz questions). Thus, queries might be a sign of reflective knowledge-building. Additional knowledge-building may be evidenced by students’ use of the explanation (EX) feature. When students ask for explanations, they can trace the reasoning that gives rise to correct or incorrect answers. By making this reasoning more explicit, the explanation feature may support refinement and revision of knowledge.

Results

Learning Outcomes

We first examined students’ concept maps. As an objective measure of map quality, we compared the maps to the expert map used by the grading system. This map had 10 concepts and 19 links, and thus had a score of 29. The average map scores (Table 1) for the ICS students; \( t(17) = -4.92, p < .001 \), and LBT students; \( t(16) = -2.12, p = .05 \), were significantly lower than the expert map score. The average SRL score was slightly higher, meaning that SRL students, included more relevant concepts and links than the expert concept map.

Table 1: Mean (SD) map scores and assessment test gains.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Condition</th>
<th>ICS</th>
<th>LBT</th>
<th>SRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final map</td>
<td></td>
<td>22.8 (5.3)</td>
<td>25.6 (6.5)</td>
<td>31.6 (6.6)</td>
</tr>
<tr>
<td>Free response</td>
<td></td>
<td>2.5 (2.5)</td>
<td>5.1 (4.6)</td>
<td>5.2 (3.4)</td>
</tr>
<tr>
<td>Mult. choice</td>
<td></td>
<td>0.4 (2.4)</td>
<td>1.1 (2.3)</td>
<td>0.4 (1.5)</td>
</tr>
</tbody>
</table>

We next compared map scores across conditions (Table 1). There was a significant condition effect; \( F(2,51) = 9.74, p < .001 \). SRL students generated significantly better maps than both ICS students; \( p < .001 \), and LBT students; \( p = .02 \). The LBT and ICS map scores did not significantly differ from each other, although LBT scores were slightly higher.

Our analysis of students’ maps suggests that receiving feedback from SRL Betty helped students to develop a more correct and complete model of the river ecosystem. Teaching Betty without such feedback was only slightly better than not teaching at all. This is consistent with the hypothesis that effective learning with teachable agents is supported by receiving active, metacognitive feedback that is reflective of the teachers’ own knowledge.

We next considered gains from pre-test to post-test on the written assessments (Table 1). We first tested whether students in each condition gained significantly on the free response and multiple choice questions. Gains for the multiple choice questions were not significant for any of the groups. However, gains for the free response questions were significant for the ICS students; \( t(16) = 3.95, p = .001 \), LBT students; \( t(15) = 6.22, p < .001 \), and SRL students; \( t(16) = 4.55, p < .001 \). Thus, all groups improved in their ability to define key ecosystem principles.

Although all groups improved on the free response questions, it appeared that the LBT and SRL students improved somewhat more than the ICS students. A comparison of the groups revealed a marginally significant effect; \( F(2,51) = 2.92, p = .06 \), but pairwise comparisons between groups were not significant.

Our concept map scores provide suggestive evidence for the benefits for the SRL-inspired pupil feedback from Betty. On the pre-post gains, the two learning by teaching groups did marginally better than the ICS group.

Student Actions

The feedback provided by the SRL version of Betty is designed to give student teachers better feedback about their own understanding, as reflected in Betty’s knowledge and performance. Receiving this feedback should also affect how students interact with Betty, hopefully leading to more productive learning and teaching behaviors.

To test this hypothesis, we examined the five main actions students could take while teaching Betty or creating their own map, such as editing the map and asking a query. These behaviors are reported as proportions of the total number of behaviors (Table 2). Table 2 also provides correlations between the given action and students’ map scores.

Table 2: Mean (SD) proportions of student actions.

<table>
<thead>
<tr>
<th>Action</th>
<th>Condition</th>
<th>ICS</th>
<th>LBT</th>
<th>SRL</th>
<th>( r(52) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM*</td>
<td></td>
<td>.65 (.12)</td>
<td>.48 (.10)</td>
<td>.41 (.08)</td>
<td>-.48*</td>
</tr>
<tr>
<td>RA</td>
<td></td>
<td>.11 (.08)</td>
<td>.13 (.08)</td>
<td>.08 (.04)</td>
<td>.09</td>
</tr>
<tr>
<td>AQ*</td>
<td></td>
<td>.08 (.07)</td>
<td>.12 (.06)</td>
<td>.22 (.05)</td>
<td>.44*</td>
</tr>
<tr>
<td>RQ*</td>
<td></td>
<td>.09 (.04)</td>
<td>.20 (.09)</td>
<td>.12 (.05)</td>
<td>.03</td>
</tr>
<tr>
<td>EX*</td>
<td></td>
<td>.05 (.06)</td>
<td>.04 (.04)</td>
<td>.13 (.10)</td>
<td>.31*</td>
</tr>
</tbody>
</table>

Group comparisons revealed interesting differences between conditions. We found significant condition effects for editing the map; \( F(2,51) = 26.85, p < .001 \), queries; \( F(2,51) = 28.98, p < .001 \), requesting quizzes; \( F(2,51) = 14.12, p < .001 \), and asking for explanations; \( F(2,51) = 8.74, p < .001 \).

The pattern that we observe is that the ICS students spent most of their time editing their map (i.e. adding and deleting concepts and links). This action was negatively correlated with map scores. Our interpretation is that these students may have focused on simply transferring facts from the text to their maps, with little reflection or knowledge-building.

The LBT and SRL students spent time editing their maps, but also engaged in a more diverse set of actions. The LBT students utilized the quizzes more often than the ICS
subsequent actions (Table 3).

In contrast, the SRL students spent significantly more time asking questions and requesting explanations than did the ICS and LBT students (all comparisons were significant at the .01 or .001 levels). These actions were specifically encouraged by the system, but not always required. As described above, querying requires students to create targeted questions about specific concepts and relationships. Requesting an explanation allows students to trace the reasoning that gives rise to questions. Greater use of these features likely reflects attempts by students to monitor and revise their knowledge, resulting in maps that were more complete and correct.

In sum, the picture that emerges is that students who received metacognitive feedback and prompts may have been supported in reflective knowledge-building, which helped them develop a better model of the river ecosystem.

**Student Responses to Feedback**

To further probe the impact of the system feedback, we also considered students’ subsequent actions after asking a query and requesting a quiz. These functions allowed the students to test whether Betty (i.e., their map) can answer questions about the river ecosystem. Varying the types of feedback available may also influence what students do after getting this information. We tabulated the total number of AQ or RQ actions and analyzed the proportions of subsequent actions (Table 3).

<table>
<thead>
<tr>
<th>Sequence</th>
<th>AQ Sequences</th>
<th>RQ Sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td>ICS</td>
<td>LBT</td>
</tr>
<tr>
<td>AQ-EM*</td>
<td>.42 (.30)</td>
<td>.40 (.12)</td>
</tr>
<tr>
<td>AQ-RA</td>
<td>.03 (.08)</td>
<td>.08 (.07)</td>
</tr>
<tr>
<td>AQ-AQ*</td>
<td>.15 (.14)</td>
<td>.17 (.08)</td>
</tr>
<tr>
<td>AQ-RQ</td>
<td>.07 (.23)</td>
<td>.14 (.09)</td>
</tr>
<tr>
<td>AQ-EX</td>
<td>.14 (.18)</td>
<td>.16 (.16)</td>
</tr>
<tr>
<td>RQ-EM*</td>
<td>.70 (.20)</td>
<td>.47 (.18)</td>
</tr>
<tr>
<td>RQ-RA*</td>
<td>.15 (.10)</td>
<td>.20 (.15)</td>
</tr>
<tr>
<td>RQ-AQ*</td>
<td>.06 (.11)</td>
<td>.07 (.07)</td>
</tr>
<tr>
<td>RQ-RA*</td>
<td>.04 (.04)</td>
<td>.20 (.12)</td>
</tr>
</tbody>
</table>

Note: Sequences of RQ-EX were not possible unless a bug occurred, and so are not included in this table.

LBT students were more likely than SRL students to access the resources after a quiz, \( p = .009 \). This response makes sense because if Betty’s answers are incorrect, then reading the text could help student learn correct ideas to teach her. One problem that might arise is if the student teacher has not understood the source of Betty’s error. A search through the text could be fruitless in that case. The SRL students were more likely than ICS and LBT students, \( p < .001 \), to ask Betty a question after getting her quiz results. This suggests that these students were attempting to more specifically diagnose Betty’s quiz performance.

In sum, our analyses of students’ actions subsequent to using the query and quiz functions support the conclusions drawn from our previous analyses. The SRL students continued to probe Betty’s understanding more effectively than did the LBT and ICS students. Not only did these students benefit from receiving the SRL pupil feedback from Betty, they might have begun to learn the value of such feedback. This could explain why they seemed to seek out additional pupil feedback when it was available.

**Discussion and Conclusions**

Learning-by-teaching provides many learning opportunities for students, but taking advantage of these opportunities places a heavy metacognitive demand. We have applied these lessons to the design of a teachable agent system, Betty’s Brain, which provides self-regulated learning feedback to cues from the agent clearer and more salient, and support students’ reflective knowledge-building and learning.

Our results suggested that the SRL-inspired feedback helped middle school students develop a more correct and complete causal model of a river ecosystem than students who taught Betty without feedback or did not teach. These results were paralleled by analyses of students’ interactions with Betty. SRL students were more likely to probe Betty’s
understanding by asking questions and having her explain her reasoning. Thus, the feedback may have supported student learning via reflective knowledge-building. These results build upon our prior research demonstrating the effectiveness of teachable agents systems for learning (e.g. Biswas et al., 2005; Leelawong & Biswas, in press; Schwartz et al., in press; Wagster et al., 2007).

Our results show that teaching an agent designed to be active and metacognitive improved learning. Peer tutors might also benefit from tutoring tutees who are more self-regulated in their learning. One way to achieve this might be to offer self-regulated learning strategy training to the tutees before they enter the tutoring setting. This is somewhat different from the usual approach, which focuses on training the tutors to use knowledge-building strategies (Roscoe & Chi, 2007). Of course, self-regulated strategy training would also likely have benefits for the tutees (Azevedo & Cromley, 2004).

These results also have implications for computer-based tutoring systems. Traditional computer tutors focus on tracking the students’ knowledge (student modeling) and tailoring feedback to fill knowledge gaps. Our teachable agent environments use students’ interaction patterns to provide feedback that is directed toward monitoring and probing the map to ensure understanding. One might say that our students are at a disadvantage because they miss out on domain knowledge feedback, but our results imply that SRL-based feedback could potentially be more effective than domain content feedback alone.

One finding was somewhat disappointing. Although all students improved their understanding of underlying river ecosystem principles (e.g. interdependence), students who received SRL feedback did not gain significantly more in this area than other students. We had hoped that supporting students’ self-regulated learning would improve their conceptual knowledge in addition to their ability to model the river ecosystem. However, one limitation of the current system is that it does not require students to teach this kind of information explicitly. For example, students teach about causal relationships involved in photosynthesis. They teach that sunlight provides energy for plants and algae, which use this energy and carbon dioxide to make food, and release dissolved oxygen as a byproduct. These relationships are clearly described in the text as part of photosynthesis, but students do not explicitly indicate this to be the “photosynthesis process” in their maps.

In future versions of the system, it may be worthwhile to expand the kinds of information that can be taught to Betty (i.e., included in the maps). For example, in addition to adding concepts and links, students may have to flag the processes these concepts and links participate in. A similar possibility would be to allow students to connect entities on their map to headings or passages in the text resources. To support the student teachers’ beneficial use of these new functions, the quiz and query functions could be expanded to directly test Betty’s knowledge of this deeper conceptual information. More importantly, the Betty agent’s feedback could be expanded to prompt students to teach her these ideas. Based on our prior and current results, increasing the scope of information that can be taught to Betty, in conjunction with her metacognitive feedback support, should lead to stronger learning gains for the students.

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References


