Modeling Learner's Cognitive and Metacognitive Strategies in an Open-Ended Learning Environment

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Abstract

The Betty's Brain learning system provides an open-ended and choice-rich environment for science learning. Using the learning-by-teaching paradigm and pedagogical agent feedback and support, the system also promotes the development of self-regulated learning strategies to support preparation for future learning. We apply metacognitive learning theories and experiential analysis to interpret the results from previous classroom studies. We propose an integrated cognitive and metacognitive model for effective, self-regulated student learning in the Betty's Brain environment, and then apply this model to interpret and analyze common suboptimal learning strategies students apply during their learning. This comparison is used to derive feedback for helping learners overcome these difficulties and adopt more effective strategies for regulating their learning. Preliminary results demonstrate that students who were responsive to the feedback had better learning performance.

Introduction

In recent years, the Betty's Brain Learning Environment (Biswas *et al.*, 2005) has been shown to add value to course instruction (Chin *et al.*, 2010) and aid learners in developing cognitive and metacognitive strategies to support science learning (Biswas *et al.*, 2010). In Betty's Brain, learners are given the task of teaching their student agent by acquiring and organizing science knowledge from hypermedia resources using a causal concept map representation (Leelawong & Biswas, 2008). As they teach their agent, they may ask her questions or have her take a quiz to assess her learning. Betty's Brain is open-ended and choice-rich: learners must decide when and how to acquire information, build or modify their concept map, check their student's progress, reflect on their own understanding of both the science knowledge and the evolving causal map structure, and seek help or feedback from a Mentor agent. Equally important is how the students sequence these activities to make their learning effective and efficient.

One important goal of working with learners in such an open-ended environment is to develop their abilities to independently regulate their learning process, a notion that supports *preparation for future learning* (Bransford and Schwartz, 1999). Cognitive science researchers have established that this preparation through development of metacognitive and self-regulatory skills is important for developing effective learners in the classroom and beyond (*e.g.*, Zimmerman, 2001). However, previous studies have shown that middle school students do not have well-developed independent learning strategies; novices often adopt suboptimal trial and error methods when they encounter difficult, open-ended, and exploratory learning tasks (Azevedo, 2005; Bandura, 1986; Schunk & Zimmerman 1997). Empirical data demonstrates that adaptive scaffolding and feedback, which address both the domain content and metacognitive strategies, can enhance learning and prepare students for future learning (*e.g.*, Azevedo & Witherspoon, 2009; Biswas *et al.*, 2010; Schwartz *et al.*, 2009).

When students reach a decision point in teaching their TA, they must determine their next step using the knowledge and strategies they possess (note that seeking help is also an important strategy (Roll, *et al.*, 2007)). Although the agents provide scaffolding and feedback to promote metacognitive strategies and science understanding, Betty's Brain is distinguished from many other intelligent learning environments because *learners are never required to make a specific, "correct" next step in order to succeed.* Instead the system provides scaffolding and support to encourage students to adopt self-regulated cognitive and metacognitive learning strategies, and, thereby become independent learners.

Properly-designed support requires understanding how students make learning choices as they perform the various knowledge-building and monitoring activities. In our

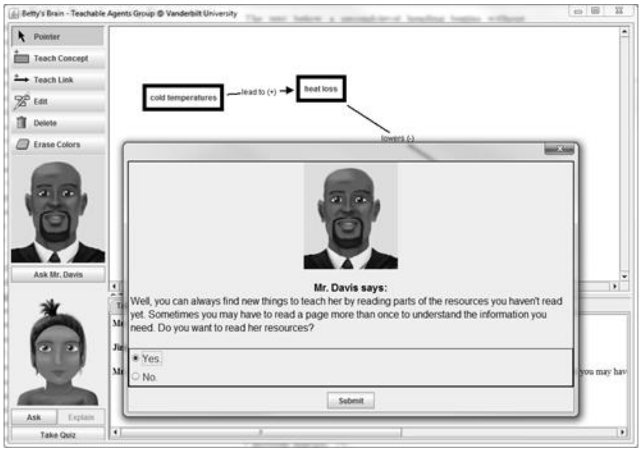

Figure 1. Betty's Brain during a conversation with the Mentor

recent work, we have explored learner choices by analyzing traces of their learning activities on the system using sequence mining techniques to discover frequent behavior patterns (expected and unexpected), and hidden Markov models to represent aggregate learning behaviors (Biswas *et al.*, 2010; Kinnebrew & Biswas, In Review). These approaches have led to some important insights about how students go about their learning tasks in the Betty's Brain system. For example, one study illustrated that students who taught their agents most effectively tended to use short sequences of reading and map editing with more queries linked to reading actions, while lower-performing students tended to use longer sequences of reading and editing with more queries linked to editing actions (Kinnebrew & Biswas, In Review).

In this paper, we apply analytical methods and experiential analyses to interpret the results from previous classroom studies (Biswas *et al.*, 2005, 2010; Kinnebrew & Biswas, 2011; Segedy, Kinnebrew, & Biswas 2011) and propose an integrated cognitive and metacognitive model for effective, self-regulated student learning in the Betty's Brain system. This model helps us interpret the deficiencies in several observed learner strategies that produce suboptimal learning. An understanding of students' suboptimal learning choices in comparison to the idealized model forms the basis for systematically defining scaffolds and feedback in Betty's Brain. In recent studies, we are gaining evidence that such scaffolds, delivered through a mixed-initiative dialog between the student and a Mentor agent, result in positive shifts in students' learning behaviors and yield significant learning gains (Kinnebrew & Biswas, 2011; Segedy, Kinnebrew, & Biswas 2011).

Betty's Brain

The Betty's Brain learning environment (*e.g.*, Biswas *et al.*, 2010), employs the learning-by-teaching paradigm to

Basic Action	Cognitive Activity
(1) Access Resources	Read domain information (*e.g.*, about entities, their role in the process(es) under study, and their relationships)
	Identify specific causal relation(s)
	Search for information (about specific concepts or causal relations)
(2) Edit Map	Add causal relation(s) between domain entities (concepts)
	Organize map (*e.g.*, group by sub-process based on concept-process associations)
	Revise causal relation(s)
(3) Query	Check indirect (*i.e.*, chain of links) relations between two concepts
(4) Request Explanation	Identify relevant links involved in answering a query or quiz question
(5) Quiz	Assess correctness of specific areas of map (by acquiring a set of correct and incorrect answers to questions posed by the Mentor)
	Gain progress feedback (from correct/incorrect quiz questions)
(6) Workbook	Note status of specific causal relation(s) (as to whether they have been checked for correctness or require checking)
	Write text notes as a memory aid (e.g., for goals, plans, and monitoring strategies)
(7) Ask Mentor	Ask for strategy advice (*i.e.*, in the current situation what strategy could the student employ to achieve their current goal?)
	Ask about the correctness of, or any problems in, the TA's answer to a question.
	Review how to organize and build causal concept maps

Table 1. Basic actions in Betty's Brain and related cognitive activities

help middle-school students learn science content while developing strategies for regulating their learning in open-ended, choice-rich learning tasks. It features both a Teachable Agent (TA), which learners teach about a science topic, such as climate change or body temperature regulation, and a Mentor agent that monitors student learning, offers advice when students initiate a conversation to seek help, and provides feedback when the learner demonstrates suboptimal learning strategies. Learners teach their TA by constructing a causal concept map, where concepts are domain entities, and links represent causal relations between entities (*e.g.*, heat reflected back to earth increases global temperature). Once taught, the TA can use the map to answer causal questions (*e.g.*, if electricity generation is decreased, what will happen to global temperature?) and explain those answers by reasoning through chains of links (Leelawong & Biswas, 2008). The TA can also take quizzes (a set of questions created and graded by the Mentor) at the learner's request. Learners know that they have completed their learning and teaching task when their TA can correctly answer all of the questions on the quiz.

As learners teach their TA, they may use several actions that are supported by the system. These *basic actions* include the following: (1) reading the hypertext resources; (2) editing the causal concept map; (3) querying the TA; (4) asking the TA to explain an answer; (5) quizzing the TA; (6) using the workbook to take notes and record important information about causal relations; and (7) requesting help from the Mentor. Using these actions, learners can accomplish several cognitive activities, such as identifying causal relationships, requesting performance feedback, and checking whether a link they created implies the right causal relation. Examples of important cognitive activities directly related to actions that can be performed on the system are listed in Table 1. These activities provide learners with a complete set of tools that they can use to accomplish their learning task.

The Integrated Cognitive and Metacognitive Model

In order to scaffold students' learning in Betty's Brain, we need an understanding of how students can employ the relevant cognitive activities (described in Table 1) to effectively and efficiently regulate their learning. Our cognitive and metacognitive model of effective, self-regulated learner behavior in Betty's Brain is illustrated in Figure 3. The model depicts an idealized set of metacognitive activities and strategies that students could employ in Betty's Brain for science learning with understanding.

The two inner layers of the model consist of the basic actions supported by the system and the relevant cognitive activities that are linked to the basic actions, as detailed in Table 1. The outermost metacognitive layer represents four related areas of metacognitive activity: (1) Goal-setting and planning to order and regulate the learners other cognitive and metacognitive activities; (2) knowledge construction, which involves processes related to acquiring information from the resources, integrating the information with existing knowledge, and teaching the new information to the TA by structuring it in the causal concept map; (3) monitoring the learner's evolving understanding of the science topic and progress in teaching the TA; and (4) help-seeking, which involves identifying the need for help and interacting with the Mentor to get advice on relevant strategies and actions.

Within each modeled area of metacognition, Figure 3 illustrates useful metacognitive strategies that are further elaborated in Table 2, which provides a general description of the strategy and its relation to cognitive activities in the Betty's Brain environment. For example, knowledge construction involves two primary strategies: knowledge acquisition or verification, (acquiring new knowledge or verifying that the current knowledge is correct) and then knowledge structuring and integration (converting knowledge to a structured form to allow for integration with existing knowledge). In the Betty's Brain environment, these strategies are often implemented by reading the appropriate section of the resources, recognizing new information as a relationship between concepts, and finally adding the corresponding link to the map.

Learner Difficulties in Betty's Brain

We hope that learners using the Betty's Brain system will employ effective metacognitive strategies as they go about their open-ended learning tasks. However, the learners in our experiments, middle school students in grades 5-8, are novices in both the science domains and independent learning (and teaching). Consequently, they encounter a variety of difficulties in their learning tasks. In particular, many of these problems manifest because students lack awareness of their own learning strategies and rarely employ effective goal-setting and planning strategies.

Consider a learner trying to teach his TA how cold temperatures trigger a hypothalamus response based on a set of resources describing the simple chain of links illustrated in Figure 2. The first sub-optimal strategy learners often employ involves *teaching information to their TA based only on their prior knowledge*. Learners often bring misconceptions and incomplete understanding to a new learning situation (Basu, Biswas, & Sengupta, 2011). If they teach these misconceptions or this partial information to their TA through the causal map, it

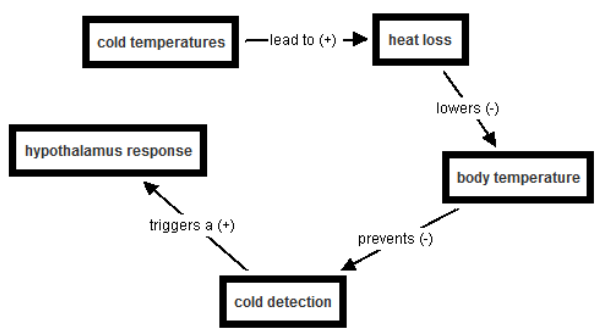

Figure 2. Example concept map for thermoregulation

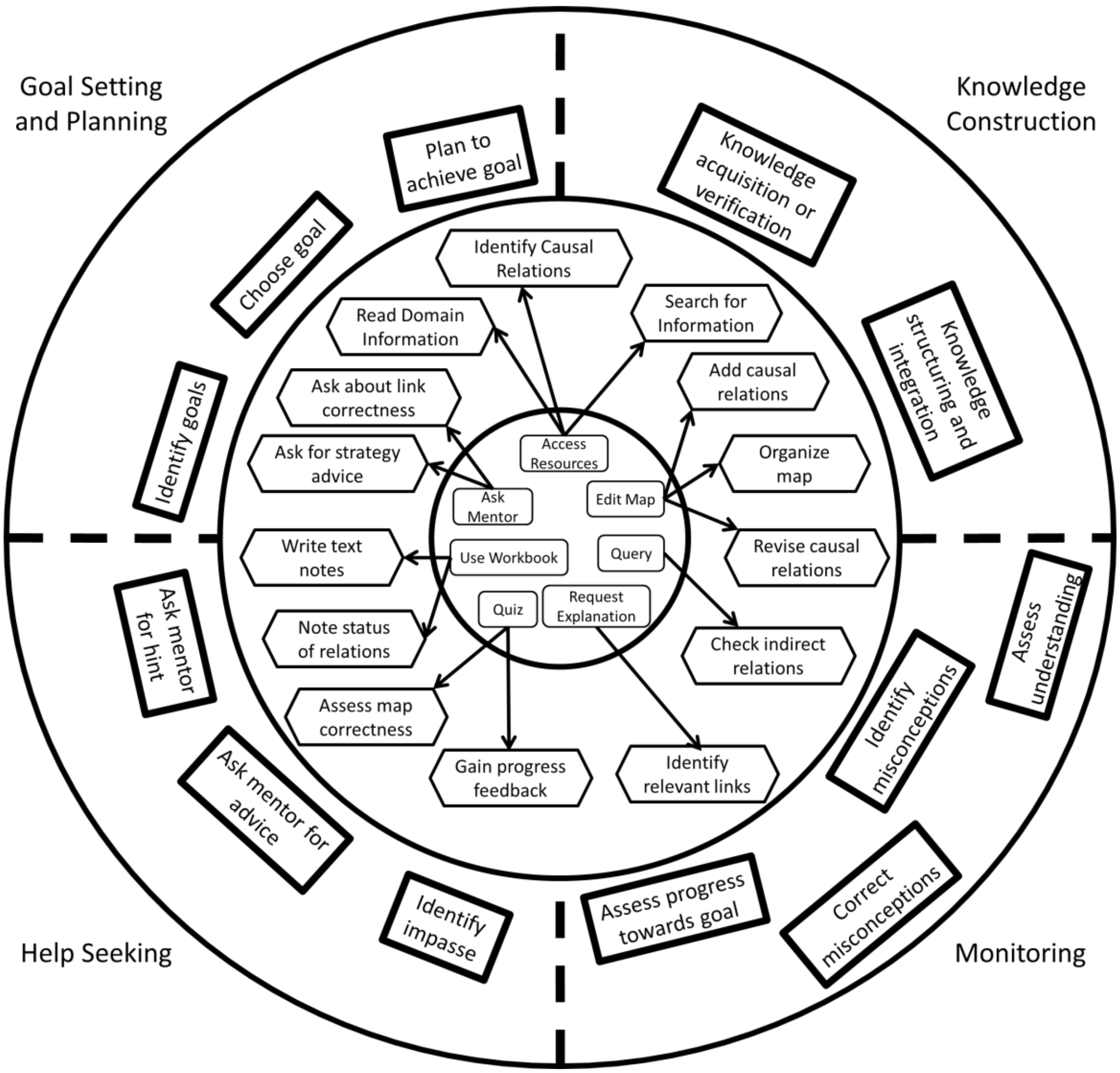

Figure 3. Integrated cognitive and metacognitive model for learning in Betty's Brain

negatively affects the TA's ability to correctly answer quiz questions. So, in the scenario above, a learner might choose to teach a link based on incomplete prior knowledge: cold temperatures increase cold detection. In this case, the learner has taught his TA correct information because cold temperatures do increase cold detection. However, adding a link that directly explains this fails to elucidate *how* or *why* it takes place. Rather, to provide his TA with complete information, the learner must explain the *process* by which cold temperatures affect cold detection, as illustrated in the map from Figure 2.

Another suboptimal strategy that learners often employ involves *utilizing quiz results for ad hoc map construction*. If our hypothetical learner, after teaching the link from cold temperatures to cold detection, were to have their TA take a quiz, the quiz would contain a question designed to point out the learner's incomplete information: "If cold temperatures increase, what happens to body temperature?" The learner in our scenario would notice that the TA was unable to answer this question, and so he may reason about what the correct answer should be. Without consulting the hypertext resources, he might reason that cold temperatures should reduce body temperature. Thus, he would teach this to his TA with a direct link from cold temperatures to body temperature.

The quiz might also contain another question the TA answered incorrectly: "If cold temperatures increase, what happens to the hypothalamus response?" The answer to this question is less obvious, so our learner decides to turn to the resources to research the answer to the question. After a quick skimming of a section of the text, he determines (incorrectly) that cold temperatures decrease the hypothalamus response. After all of this work, our learner's map looks like the one shown in Figure 4.

Metacognitive		Integration	Cognitive
Metacognitive Area	***Metacognitive Strategy/Activity***	***Applying Cognition and Metacognition***	***Supporting Cognitive Activities***
Goal-setting & Planning	Identify goals	Read introductory, overview, and organization material to identify different sub-processes or integration of sub-processes	Read resources
	Choose goal	Consider incorrect questions to identify sub-process with few or no answers correct on quiz	Gain progress feedback by taking quiz
	Plan to achieve goal (*e.g.*, understanding and teaching TA about sub-process)	Skim introduction to sections and organization material to identify relevant resources for goal	Read resources
		Take notes about which resources to read and relevant strategies to apply in achieving goal	Write text notes as a memory aid
Knowledge Construction	Knowledge acquisition/verification	Read identified resources relevant to goal	Read resources
		Determine causal relations from reading	Identify causal relation(s)
	Knowledge structuring and integration	Edit map to add links for identified causal relations	Add causal relation(s) to map
		Reorganize map by concept-process association	Organize map by sub-process
Monitoring	Assess understanding	Check direct and indirect relations that involve recently added links against current understanding	Check direct links by re-reading resources, and indirect relations by query, quiz, and explain activities
	Identify misconceptions and incomplete representations	Identify overlap in links between correct and incorrect quiz questions	Identify relevant links
		Note links from correct answers as checked and unchecked links from incorrect answers as needing to be checked	Note status of causal relation(s)
		Find resource material to check identified links	Search for information
	Correct misconceptions and incomplete representations	Determine corrected/ replacement relations	Identify specific causal relation(s)
		Correct/replace links for identified causal relations	Revise causal relation(s)
	Assess progress toward goal	Assess change/progress on questions related to current goal and recent edits	Gain progress feedback
Help-Seeking	Identify impasse or difficulty	Identify inability to progress toward goal or correct misconceptions based on quiz results	Gain progress feedback
	Ask Mentor for specific advice	Initiate conversation with Mentor and direct conversation based on current goal and difficulties	Ask for relevant strategy advice
	Ask Mentor for hint	After the TA has explained her answer to a causal question, ask the Mentor if the explanation contained any problems.	Ask about correctness

Table 2. Metacognitive and cognitive activities in Betty's Brain

At this point, the learner's map has a number of errors, and this further confuses him because he is unable to pinpoint a source of error that he can correct. When he has his TA take a quiz again, the TA gets the same questions wrong, even after he seems to have taught the TA how to answer them correctly. As a result, the learner reaches an impasse. He has lost confidence in his approach and his plans to continue building the map.

At this point, our hypothetical learner may resort to another suboptimal strategy: "*guess and check*," in which he removes a link, adds a link, or changes the sign on a link and then checks whether his TA's performance improves. For example, every time he has his TA take a quiz, he finds a link related to one of the wrong answers, makes a simple uninformed edit (*e.g.*, switching the link

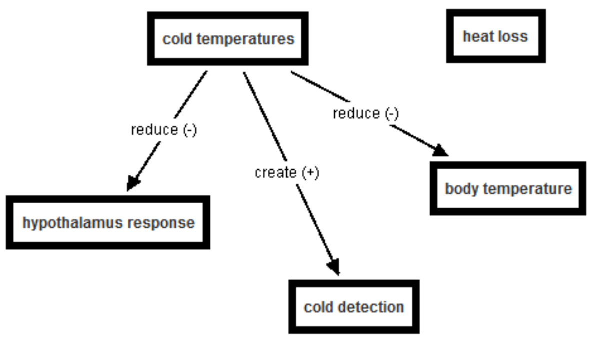

Figure 4. Example student concept map with errors

from increase to decrease) and then takes another quiz. However, this confuses him more as his TA's quiz results have the same number of errors. Moreover, some questions that his TA answered correctly on previous quizzes are now being answered incorrectly (because of his uninformed edits), and this naturally leads to discouragement, frustration, and further loss of confidence. Therefore, at the end of this exercise, our learner has learned very little about thermoregulation, and he spent a large portion of his time using suboptimal learning strategies, which naturally limited his opportunities to learn.

Such a scenario represents real problems that many learners have faced while using Betty's Brain. Difficulties such as these have led other researchers to argue that open-ended and constructivist learning environments may hinder learning (e.g., Klahr & Nigam, 2004). However, we believe that our approach, if properly scaffolded, will equip learners with an important understanding of how to assimilate and represent difficult scientific information, better preparing them for future learning. Therefore, the next section compares the idealized metacognitive strategies from our model to the common suboptimal strategies employed by the learner in our scenario. Based on this comparison, we derive conversational feedback for guiding learners toward more productive learning strategies.

Using Feedback to Guide Learners Away From Ineffective Strategies

If we were to look back to our example learner, how might we characterize his strategies in light of our model (see Figure 3)? His first suboptimal strategy was a knowledge construction strategy that involved *teaching prior knowledge without reading the hypertext resources to check if he was building an accurate model*, which resulted in his teaching incomplete information to his TA. It is important to note here that the learner's decision to teach without reading is not necessarily an ineffective choice; learners may prefer to start by teaching their current understanding before they begin reading. However, when the learner makes choices that, over time, continue to negatively impact his performance (*e.g.*, the quality of his causal map), feedback can encourage him to modify his strategy, and help him improve his learning.

Once we decide to give feedback, we can analyze the difference between his learning strategy and those contained in our model. In this case, the learner's strategy is negatively impacting his teaching (and learning) by adding incorrect or incomplete information to the map. One strategy suggested by the model involves first *acquiring information or verifying prior understanding*, and then *structuring it* by teaching the TA. Therefore, the Mentor agent might recommend that the learner adopt this strategy. He might say: "*Hey Jake! I've noticed that you're teaching information you haven't read about. How do you know that you are teaching your student the right links for her to understand thermoregulation*?" Feedback such as this encourages the learner to reflect on his approach to learning and teaching, which, with additional support from the Mentor agent in understanding effective metacognitive strategies, can lead to the adoption of a better strategy.

Our learner's second sub-optimal strategy was a monitoring strategy that consisted of *utilizing quiz results for ad hoc map construction*. The learner monitored his progress by having his TA take a quiz, and then he used the result of that quiz to systematically teach several direct relationships between concepts that should not have been directly connected in a complete representation of the process. In our experience, learners who employ this strategy have a misconception about how to use the TA's quiz results to identify problems and incomplete representations. Further, this may be related to a lack of understanding on how to model a scientific process. Thus, when such an approach is detected (*e.g.*, by comparing link adds to recent quiz results), the Mentor agent can again interact with the learner, saying *"It looks like you're trying to help your TA do better on her next quiz. Would you like some help doing this?"* Should the learner agree, the Mentor might give the student choices on the feedback content, such as (a) *learn how to construct causal maps*, and (b) *how to interpret quiz results*, among others. If the student chooses (b), *i.e.*, how to interpret quiz results, the Mentor would continue by explaining a key insight (*e.g.*, when the TA correctly answers a quiz question, all of the links in her explanation are correct) in the context of how it can be applied to the current situation. The Mentor might also highlight the explain button while reminding students that when the TA explains an answer, she indicates exactly how she generated her answer. Such feedback is directed to teaching learners a valuable monitoring strategy while also helping them achieve better results in their teaching and learning tasks.

Finally, our learner's last ineffective strategy involved several iterations of first taking a quiz to receive performance feedback, and following that with an uninformed edit. This "*guess and check*" approach to map building generally indicates that the learner has reached (or will soon reach) an impasse: he has lost confidence in his approach, his self-efficacy is suffering, and as a result he is gradually disengaging from the learning task. In terms of the model, our learner is (1) using a highly-ineffective monitoring strategy, (2) no longer participating in any significant planning or goal-setting activities, and (3) choosing not to seek the help that he needs to move forward.

Feedback delivered by the Mentor at this time needs to accomplish three things. First, it should help the learner understand and *re-establish* his current goal as a context for moving forward. It should also *provide positive feedback* on work done so far in order to restore some of the learner's self-efficacy. Finally, it should *provide a relevant suggestion* for moving forward, giving the learner the help and push he needs to re-engage in the learning task. As an example, the Mentor might say "*Hey Jake. Can I help you? I think that if we work together we can make sure that your TA learns everything she needs to know*." Upon affirmation from the learner, the Mentor might continue: "*Remember, you need to read in order to learn what to teach your TA. You've already taught her some good information, but there are also some links on her map that are confusing her. If you'd like, I can help you by picking out an incorrect link and explaining why it's wrong. Would you like me to do that*?" Feedback such as this has the potential to help learners who have reached an impasse and are no longer confident in their ability to accomplish the task.

Overall, our cognitive/metacognitive model provides a framework for analyzing learner behaviors and understanding learner difficulties in relation to effective, self-regulated learning strategies. Further, this comparison guides the development of feedback designed to help students overcome the obstacles in their open-ended learning task. We believe that feedback developed in this manner will enhance both science learning and preparation for future learning with the Betty's Brain learning environment.

Identifying suboptimal strategies and designing agent feedback based on this model have shown promise in initial classroom studies (Segedy, Kinnebrew, and Biswas, 2011). In particular, analysis of a recent study with 7th-grade students in middle Tennessee science classrooms indicated a statistically significant correlation between normalized learning gain and students' decisions to continue a dialogue with the Mentor agent when offering strategy feedback. Similarly, analysis of students' actions following this strategy feedback indicated a statistically significant correlation between normalized learning gain and actions consistent with the Mentor's advice. Moreover, these correlations were both stronger than the correlation between normalized learning gain and students' prior performance on standardized academic tests. These preliminary results illustrate the potential of the feedback designed through comparison of students' suboptimal learning strategies with the presented cognitive and metacognitive model.

Conclusion

In this paper, we have presented a cognitive and metacognitive model for effective learning strategies in the Betty's Brain learning environment. We further applied this model to interpret three commonly-observed difficulties that learners face while using the system. This comparison motivated the development of feedback to help learners overcome obstacles and engage in effective learning in an open-ended learning environment. We believe that such feedback, when delivered through a conversation with the Mentor agent and contextualized by the learner's current activities, encourages learners to practice and develop effective strategies for navigating open-ended learning activities.

In the continuing development of Betty's Brain and future classroom studies, we will apply our model to additional learner difficulties in order to develop a more comprehensive collection of feedback for both scaffolding learning in open-ended learning environments and promoting metacognitive, self-regulatory skills. This scaffolding and feedback is crucial to our goal of empowering students to take control of their learning as they practice using effective learning strategies.

Another important avenue for future work involves employing the cognitive and metacognitive model to systematically interpret activity traces of learners while using Betty's Brain. In particular, interpreting the cognitive and metacognitive states represented in hidden Markov models derived from student activity traces (Biswas *et al.*, 2010) with respect to this model may yield a deeper understanding of student learning strategies and how to detect suboptimal strategies in Betty's Brain.

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