Human Tutoring as a Model for Computer Tutors: Studying Human Tutoring from a Cognitive Perspective

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Abstract. Recent advances in research on learning through discourse in conceptually rich problem-solving domains is making it possible to study cognitive processes, reasoning, and knowledge representations in interactive problem-based learning environments. Research is focusing on analysis of expert tutoring and tutor-supported learning processes in such domains as statistics and engineering. Examples of such studies in the domain of statistics will be presented to illustrate how a cognitive science methodology based on the psychological study of discourse processing, reasoning and problem solving can lead to the development of explicit models of expert tutors' knowledge, explanations, dialogue, and tutoring strategies, and of the processes involved in tutor-supported problem-based learning. The resulting models of expert human tutoring can be used to design computer tutors to emulate aspects of natural tutoring. Current work in progress in our laboratory will be used to illustrate the design of such a tutor.

1. Introduction

Instructors in complex domains of conceptual knowledge and problem-solving (e.g., in university courses in domains such as applied statistics) are increasingly adopting more problem-based and collaborative approaches to instruction. In such instructional situations instructors typically adopt a role of tutor, mentor or coach, creating conditions of cognitive apprenticeship. Researchers analyzing interactive discourse in problem-based learning situations such as human tutoring: [1], [2], [3], [4], [5], [6], [7], are contributing increasingly detailed models of the cognitive and social processes by which problem-solving knowledge and expertise develop and are supported by mentors in these kinds of instructional environments.

Computer-based coached learning environments can be designed to embody forms of coaching and interaction with students, and ways of articulating and explaining problem-solving knowledge, that are similar to and reinforce those of experienced and effective human tutors. The challenge is to provide appropriate kinds of tutoring support to help students as they learn to function effectively in complex problem-solving environments. In this paper, we report progress in developing a methodology for authoring web-based computer coaches that emulate (a) tutor modeling of problem solving processes, (b) embedded tutor explanations, and (c) coaching support found in studies of expert human tutoring. A method of tutor development will be described in which a database of tutoring knowledge is created (for a particular subject-matter domain) on the basis of analysis of tutorial dialogue in natural problem-solving situations.

2. The Statistics Tutoring Situations

As a starting point for developing a computer coach that emulates expert tutoring, we analyzed tutorial dialogue and students' problem-solving within natural tutoring situations in applied statistics. These include: (a) face-to-face tutoring of individual students (in which the tutor and student share the use of statistical software and the tutor uses the software and prepared data files to demonstrate and explain how to use ANOVA to solve data analysis problems); (b) networked one-to-one tutoring (in which the tutor introduces a student to analysis of variance (ANOVA) in the same manner as in the face-to-face condition but communication is by means of video-conferencing software); and (c) "bystander learning" in which pairs of students learn while viewing the tutor-student dialogue as it occurs over a network. In each of these situations, students' shared the use of statistical software as they learned to use ANOVA to solve a series of problems which included data sets to be analyzed. A stack of "blackboard" representations (e.g., graphics, equations, tables, and other displays) were provided as resources for the students as they are were tutored by an experienced faculty member. The students were tutored in ANOVA theory and methods, and in how to use statistical software for data analysis. The tutor was an experienced instructor with a reputation as an outstanding teacher who specializes in the use of problem-based teaching methods.

3. Discourse Analysis and Modeling of Tutorial Dialogue

Our discourse analysis methodology reflects the application of a model of discourse representation and processing that was originally developed in research on text comprehension and production: [8], [9] to interactive discourse: [10], [11]. The tutorial dialogue is analyzed as a sequence of transactions between the tutor and the student that involve different topics in ANOVA. These transactions reflect: (a) the problem-solving methods of the tutor and the student; (b) various kinds of tutor help (including instruction in problem solving, conceptual explanations, and coaching assistance) provided interactively to the student; (c) the propositional content of embedded tutor explanations of ANOVA; and (d) the conversational structure of the tutorial dialogue. The steps in the discourse analysis of the transcribed tutorial dialogue were as follows:

3.1 Topicalization.

Natural tutoring situations can involve multiple sessions lasting as long as an hour. After transcribing the sessions (using transcription conventions similar to those used in Conversation Analysis), the dialogue is segmented into thematic units corresponding to particular topics in ANOVA. These sequences are very useful in mapping the instructional sequence used by the tutor in global terms, and in locating information in subsequent analysis. They are also useful in authoring the tutor database and in the creation of a glossary as a component of the computer tutor. Table 1 presents an example of the topic sequence for the tutor's review of one-way ANOVA for a novice student.

Table 1
Discourse Fields on ANOVA Procedure Frame: Tutoring Session 1
Tutor's Review of One Way Analysis of Variance

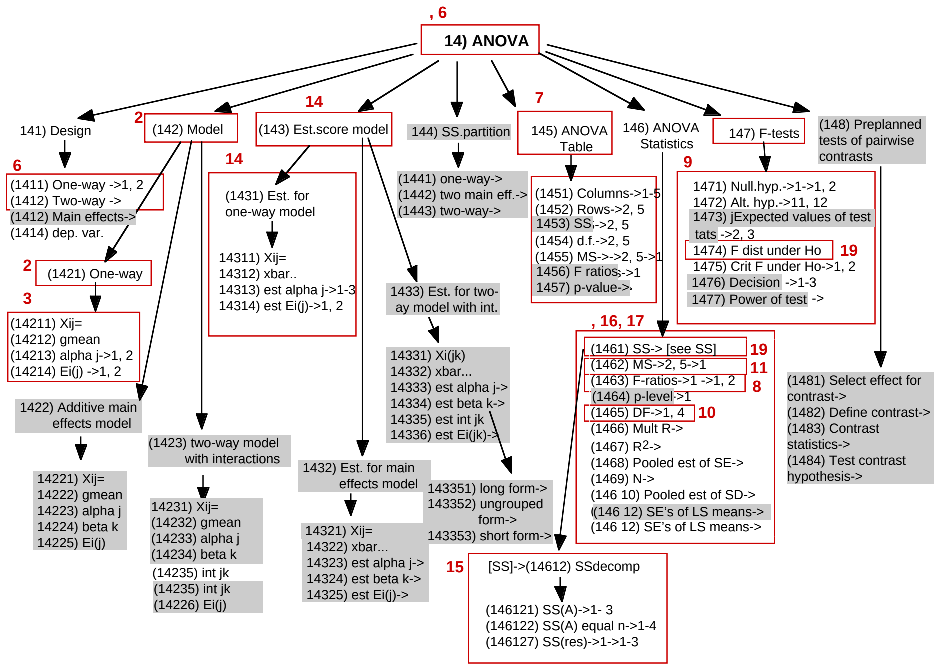
Segments	Topic
1-15	Beginning of Tutorial Session
17-38	1. Introduces Data Set for Analysis
39-162	2. Introduces Descriptive Statistics on Data Set
163-215	3. Explanation of Standard Error of the Mean
216-243	4. Discusses Use of Descriptive Statistics to Locate Significant Differences among Means
244-267	5. Preparations of SYSTAT for Doing an ANOVA
268-323	6. Begins Discussion of How to Run the ANOVA using SYSTAT
324-394	7. Begins Discussion of Output of SYSTAT ANOVA
395-503	8. Begins Explanation of F-Ratio's
504-594	9. Begins Explaining Hypothesis Testing Procedure
595-651	10. Explains Degrees of Freedom
652-719	11. Explains Mean Squares
720-768	12. Introduces ANOVA Table
769-787	13. How to Write the Model Equation
788-891	14. Discusses Estimates of Effects in ANOVA Model
892-966	15. Explanation of Sums of Squares
967-1001	16. Explanation of Mean Squares
13-53	17. Discussion of Mean Square
243-660	18. Discussion of Results of ANOVA for Problem One
660-661	19. Explains MS between & within, Expected F under Null Hypothesis

3.2 The Procedure Frame: Modeling Problem-Solving Methods

The macrostructure of tutorial dialogue reflects the structure of the plans and actions used to solve problems during the instructional sessions. Models of the procedures used to perform these tasks are constructed from a cognitive task analysis of the domain, independently obtained problem-solving protocols, and the tutorial dialogue and accompanying problem-solving actions. These models employ the formalism of a hierarchical tree structure or "planning net" to define a hierarchical *procedure frame* representation of the network of actions and goals which are required to perform the task or solve the problem: [9], [12]. This frame represents a model of the component procedures used to solve a problem. Nodes represent component procedures (i.e., subtasks), vertical links relate procedures in terms of their decomposition into subprocedures, and horizontal links identify conditional or temporal order constraints on the execution of component procedures within a branch of the tree. The sequence in which the component procedures are applied defines a trace of the solution procedures used in the tutoring session.

Figure 1 presents the decomposition structure of one node in the expert frame as it was reflected in the tutor's dialogue with the novice student (as topicalized in Table 1). The topics for this session are mapped onto this frame. The numbers superimposed on the hierarchical frame represent the sequence in which component procedures were introduced into the dialogue. Shaded nodes were not covered in this tutoring protocol since only one-way ANOVA was covered in this session. In general, the tutor's modeling and explanation of the ANOVA frame through his dialogue with the students was systematic and relatively complete in its coverage of the procedures.

Figure 1[1]
Tutoring Session One - Review of One Way Analysis of Variance (cont.)



3.3 Types of Tutor Help.

Through tutorial dialogue accompanying problem-solving actions, tutors typically provide a variety of types of information and coaching assistance with the component procedure (subtask) being applied. *Types of descriptive information* about any sub-procedure include: descriptions of the *action*, the *goal*, the *problem state*, the *result*, *conditions* for applying the procedure, *explanations* of the sub-procedure, and instruction on how to use any *tools* (i.e., the statistics software) that are needed to apply the procedure. *Explanations* were found to be of several types including explanations of: (a) relevant statistical *concepts*, (b) *theory*, (c) *representations* used or obtained in the analysis, (d) the procedure itself (including *goals*, *actions*, and *results*), and (e) *pragmatic* considerations related to how the procedure is used in the real world. In addition, the tutor's *coaching strategies* were found to involve (a) *guidance* in what

[1] From Frederiksen, C. H. & Donin, J. (1999). Cognitive assessment in coached learning environments. *Alberta Journal of Educational Research*. XLV (4), 392-408. Used with permission.

specific procedures to apply, (b) *assistance* with specific procedures, (c) *prompts* such as *questions*, *clarifications*, and *hints*, and (d) *feedback* on the students' results.

3.4 The Structure of Embedded Explanations.

Our analysis focused specifically on the content of the tutor's embedded explanations. We focused on the conceptual structure expressed through the propositional content of the tutor's explanations, and how these explanations were linked to the procedure frame (i.e., where they were embedded in the procedures, and how they were used to provide conceptual links across different aspects of the ANOVA procedures). We were also interested in how the tutor modeled the reasoning processes involved in statistical inference in ANOVA.

A good example of how explanations of concepts and theory served to link ANOVA procedures is given by a short tutor explanation of the F ratio to the novice student:

387 Ok, this-, ok, F ratios, ok, can be assumed under the null hypothesis to have a certain distribution, ok, (DRAWS AXES ON BOARD) for things like-, and there-oh let me go back a bit ((farther)).

388 The shape of an F ratio-, the precise shape of an F ratio (POINTS TO F-RATIO IN SYSTAT ANAYSIS WINDOW)depends on the degrees of freedom that you have here. (POINTS TO DF IN SYSTAT WINDOW)

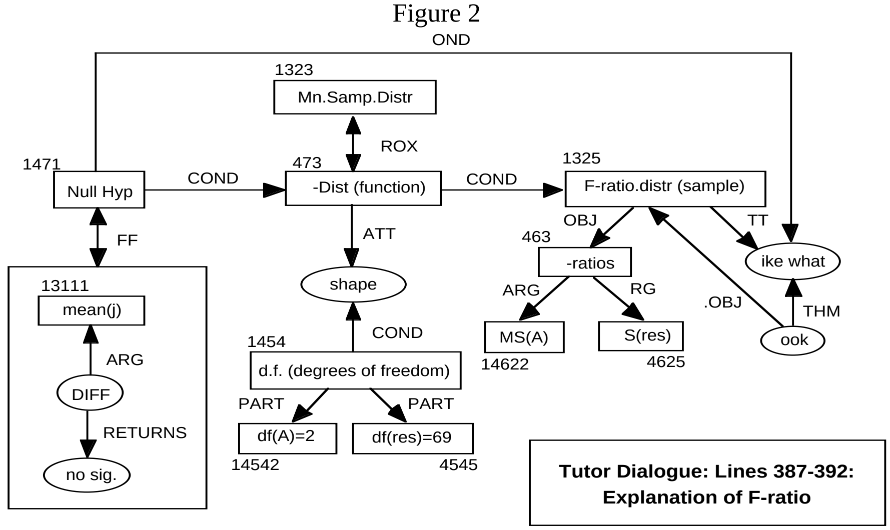
389 Ok, and here we have 2 and 69 degrees of freedom..

390 Now what-, what the F distribution specifies is a lot like the sampling distributions of the mean that we talked about.

391 The F distribution specifies what the ratio of these mean squares (POINTS TO MS VALUES) would look like under the null hypothesis.

392 That is, there being no significant difference, ok, among the means.

Figure 2



The conceptual structure of this explanation (based on a propositional analysis) is given in Figure 2. Here the Procedure Nodes are denoted by rectangular boxes, and other concepts are given in ellipses. The tutor has established conditional links from the null hypothesis to the F distribution (which is conditional on the null hypothesis) to the sampling distribution of the F ratio (under the null hypothesis). The null hypothesis is linked to the sample mean differences, the F distribution is linked to the degrees of freedom and to the sampling distribution of the mean, and the sampling distribution of the F-ratio is linked to the F ratio. Thus, this short explanation has linked a number of key concepts in ANOVA into a well-defined conceptual structure, one which depicts the chain of reasoning involved in hypothesis testing in ANOVA.

3.5 The Interactive Structure of the Tutorial Dialogue

Analysis of the conversational structure of the tutorial dialogue begins with an analysis of turns and turn-taking, and an analysis of the functions of the participants' conversational speech acts within the conversation (Searle, 1969, 1979) using a coding system adapted from one developed by Dore (1979). We focused specifically on conversational sequences involving assertions, requests, responses, and expressives. In addition, we categorized the extent to which the tutor adjusted the content of his dialogue to reflect the student's dialogue as: *non-contingent* (continuation of a topic preceding a student utterance or action with no adjustment contingent on the student) and *contingent* (the tutor's utterance is adjusted to the students' utterance with an *indirect response* (e.g., a topic shift or elaboration of a current topic) or *direct response* (e.g., a response to a direct student request, agreement or disagreement, or acknowledgment of the students utterance or action).

While there was a high degree of consistency of the sequence in which procedures were introduced and in the structure of tutor explanations and help, there was also adaptation to individual students. Since this adaptation took place through tutor-student dialogue transactions, we examined the types of conversational interaction that occurred (in terms of types of conversational acts and sequences), and second, the extent to which the content of the tutor's discourse was contingent on the content of the students' discourse. The analyses revealed that that the tutor adapted the content of his discourse to the student on the basis of information gained from the student's speech and actions. At the same time, he pursued his planned explanations and modeling of problem-solving knowledge.

4. Development of the Computer Tutor

To construct the tutor we have been using a program that we developed (called "Tutor Builder") to author a database of tutoring knowledge from our analysis of the tutor's demonstrations and explanations of how to solve data-analysis problems in statistics. This program provides a tool for the construction of a hierarchical data structure consisting of a large number of HTML files that contain information about component procedures (similar to that provided by the human tutor). While students run a statistics program to analyze a practice data set on their computers, they can access the

ANOVA Tutor database concurrently on a remote server using a web browser. Students can use the browser to view and interact with a hierarchical guide to the organization of problem-solving actions. They can also view multimedia messages from the tutor explaining particular steps in solving data analysis problems. In this way students can use the tutor to obtain instruction and coaching support as they practice solving data analysis problems on their computer.

We are currently implementing this tutor as a relational database of tutoring knowledge on a Mac OS X Server using Web Objects to create a user interface for interacting with the tutor database. This enhanced tutoring environment will allow students to “ask for” and receive instruction, explanations, or coaching from the tutor, submit their work on practice problems, view expert solutions, learn to self-evaluate their own work, and receive feedback on their errors or misconceptions. Furthermore, the Web Objects implementation of the tutor can be used both as a tutor authoring environment (by a developer) and as a learning environment (by students).

4.1 Constructing the Database of Tutoring Knowledge

The Tutor Builder software was used to develop a database of tutoring knowledge that is structured according to the ANOVA procedure frame. This database is organized in terms of the procedure hierarchy, and associated with each node (i.e., component procedure) there are "semantic fields" that contain text and graphic information about the procedure. This information is based on types of descriptive information that was provided by the tutor through his contributions to the tutorial dialogue. In the computer tutor, semantic fields provide two kinds of assistance to the student: Instruction and Coaching. Instruction provides several kinds of semantic descriptions of component procedures: Goal Descriptions, Problem State Descriptions, Action Descriptions, Tool Instructions, Theory Explanations, Conditions (necessary for carrying out the step in the procedure), and Result Descriptions. Coaching Assistance is provided in the form of Questions, Clarifications, and Hints.

As an example, consider the Tutor Window presented in Figure 3. The panel at the lower left of the Window provides the student with a "Procedure Map" of the hierarchical structure of the procedure (like a site map on the internet). The student can select any node (i.e., component procedure) from the map, and then "request" coaching assistance or instruction pertaining to the selected procedure by selecting a type of assistance (from the panel immediately above the Procedure Map). For example, types of instruction include a statement of the Goal of carrying out an ANOVA, a description of the kinds of Results obtained from doing an ANOVA, or an explanation of the relevant Theory. Coaching is provided at several different levels and the student can select the level of assistance he or she desires: Questions, Clarifications, or Hints (up to three levels of hints are available). Once a type of instruction or coaching assistance has been selected, the tutor displays the relevant text or graphic information in the right panel of the window. The buttons in this panel provide access to other types of instruction or levels of coaching. It is possible to provide graphics, sound, and even movie clips to accompany these windows. Glossary items are highlighted in the presented text, and an alphabetized listing of all glossary items is always available by means of a pop-up selection window.

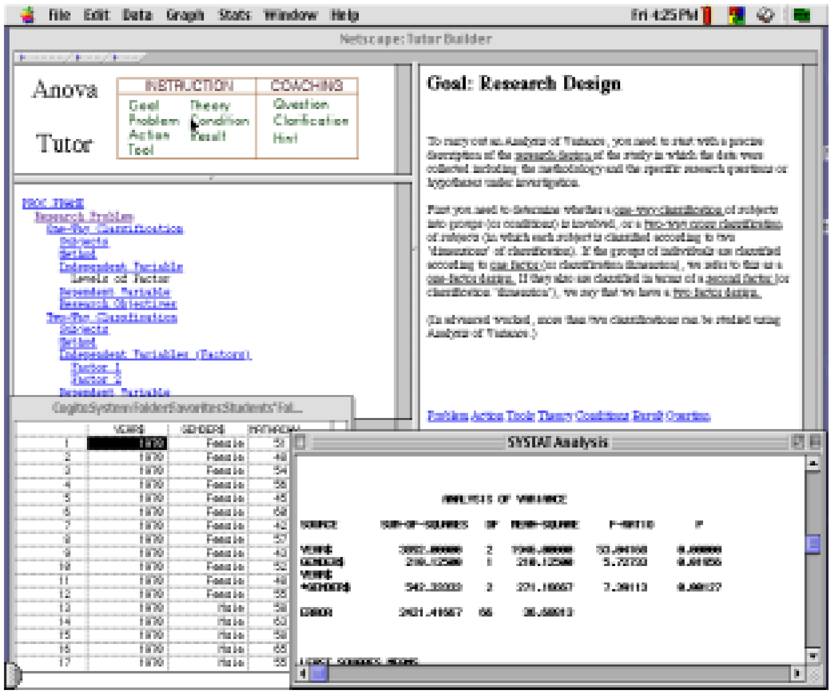


Figure 3[2]

The computer coach is run concurrently with the statistical analysis software. The student is presented with a prepared data set and a description of the data, how the data were obtained, and the purposes of the study. The problem-solving task involves planning and executing a complete analysis using the statistical software, and submitting a report containing results obtained at each step (the report is organized as a sequence of student responses to tutor-supplied questions). The student can cut and paste information from any tutoring window, or from the statistical environment (e.g., results from the output window) into the template, and enter information using text editing functions. This environment closely parallels that used in the natural classroom and tutoring situations. The students work independently or in groups on problem exercises while using the tutor. Their task is to learn to produce correct analyses independently and produce accurate and complete reports by practicing these exercises (with the help of the tutor).

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[2] From Frederiksen, C. H. & Donin, J. (1999). Cognitive assessment in coached learning environments. *Alberta Journal of Educational Research*. XLV (4), 392-408. Used with permission.

4.2 Authoring the Content of Tutor Explanations and Instruction

The content of tutor help provided by the computer tutor is developed to accurately reflect and enhance that which is found in the tutorial dialogue of the expert tutor. The authoring process is carried out from the top (of the procedure hierarchy) down, and reference is made to the tutorial dialogue as each of the content fields ("semantic fields") is filled with a relevant "tutor message". To illustrate this process, the semantic fields written for the Score Model Procedure (142) are as follows:

Question. What is the ANOVA score model for your research design?

Clarification. In ANOVA models, scores on the dependent variable for each individual are decomposed into several additive components. Specifying the score model requires that you specify each of these components for your design.

Hint 1. The components of the scores include effects of the independent variable(s) or factor(s).

Hint 2. In addition to effects, the score model also includes a constant term.

Hint 3. Finally, the score model also includes a residual or error component.

Goal. Specify how the score model breaks down each score into additive parts.

Problem State. You have already specified your ANOVA design. This means you know what your factor or factors are and the levels of each factor. You also know what your dependent variable is.

Action. Choose an individual observation from any group in your data set and write the score model as a linear equation for that observation. Do this for one individual from each group. Finally, use appropriate subscripts to write a single equation that could be applied to any individual from any group.

Conditions. In order to specify what the components of a score are you need to know what effects enter into the decomposition of scores for a particular individual within a particular group.

Result. The score model for a given individual observation will be a linear equation which includes on the left hand side a variable indexed to indicate which individual i's score is being decomposed along with a second index of the individual's group j. The right hand side of the equation consists of additive terms including the grand mean, the effect of the individual's group (on the subject's score), and the residual or error component of the individual's score.

Theory. Analysis of variance provides a method for analyzing which part of a person's score is attributable to his or her group classification (i.e., the group mean), and which portion is due to the deviation of his or her score from the group mean (i.e., the residual or error component). This can be expressed as the following equation:

$$(1) \quad x_{i(j)} = \mu_j + e_{i(j)}$$

Greek letters, e.g., μ_j , refer to population parameters that will be estimated from the sample data. In this case μ_j refers to the population mean for group j.

Notice that the error score $e_{i(j)}$ for individual i is expressed as a deviation from the mean μ_j of his or her group j.

In ANOVA we want to express the group mean as a deviation from the overall mean so that it too can be interpreted as a deviation score.

Therefore, we can subtract the general mean (i.e, the grand mean μ) from both sides of the equation — thereby expressing the linear score model in terms of deviations of an individual's score from the general mean:

$$(2) \quad x_{i(j)} - \mu = \mu_j - \mu + e_{i(j)}$$

The term (μ_j - μ) can be grouped:

$$(3) \quad x_{i(j)} - \mu = (\mu_j - \mu) + e_{i(j)}$$

The term (μ_j - μ) is the deviation of the group mean from the general mean and is a constant for everybody in group j. In ANOVA models this is called an "effect" and is conventionally represented by a Greek letter (starting with alpha for the first effect).

$$(4) \quad x_{i(j)} - \mu = \alpha_j + e_{i(j)}$$

Finally this equation can be written in terms of the original score as:

$$(5) \quad x_{i(j)} = \mu + \alpha_j + e_{i(j)}$$

The score $x_{i(j)}$ is made up of the overall mean of the population μ, plus an effect of the group α_j, plus a residual (or error) score $e_{i(j)}$. This equation is called the ANOVA score model.

The parameters μ and α_j must be estimated using the sample data. This is done using the estimator version of the score model. Once these estimates are obtained, they can be used in the model equation to obtain the residual score for each subject.

Comparison of the content of the authored tutor explanation of the score model in the computer tutor to that of the human tutor reveals both similarities and differences. The computer tutor explanation includes the same links to other procedures (e.g., data, design model, descriptive statistics, and the estimator version of the score model) as were found in the natural tutor explanations. Moreover, the final score model is described similarly and the score model is linked to the data and to the group means. However, unlike the natural tutor explanations, the explanation is more self-contained and does not skip directly to the estimator model. A natural tutor can make intentional use of implicit links by controlling movement between topics, where in the computer tutor, the link (e.g., to the estimator model) is mentioned but to receive tutor explanations of the estimator model the student must navigate to this procedure (using the procedure map) or consult the glossary entry.

The computer tutor is more complete (i.e., the natural tutor does not provide complete information in any one tutoring situation). For example, here it includes a *conceptual bridge* from (a) an equation expressing a subject's score in terms of the group mean and a deviation from the group mean (a link to the descriptive statistics procedures; Equation 1), to (b) the ANOVA score model (Equation 5). This bridge shows how the ANOVA score model is obtained as a "re-parameterization" (in the terminology of statistics) of the "mean score" model. This explanation completes and makes explicit links that the human tutor included in his explanations. Finally, the tutor explanation is presented in general terms (rather than in terms of the specific problem example and data being analyzed). Problem-specific information is stored separately in the tutor database and can be viewed when students submit their work and view an "expert solution" for the subtasks just completed. A student can compare his score model for a specific practice problem to an "expert score model" for the problem and receive explanations of any errors.

Other types of tutor messages such as statements of goals, descriptions of the problem state, actions, conditions, and results are always available from the computer tutor, whereas they are often not provided by the human tutor. Nevertheless, the content of these messages is similar to that normally provided by human tutors. This is a second way in which the computer tutor is more complete. We assume that expert tutors have such knowledge although it is highly unlikely that all of this knowledge will be expressed in any given tutoring session. To check this assumption, we are including an expert review of tutor content in our development process. Indeed, we envision that tutor authoring using our Web Objects application and tutor database schema will be done eventually by experts themselves.

Coaching support is provided through questions, clarifications of questions, and graded hints similar to those used by human coaches. Data obtained on coaching ANOVA are used to help in authoring the coaching content. Finally, the computer tutor replaces tutorial dialogue with panels which allow a student to “request” and receive help messages (of various kinds) from the computer tutor. The computer tutor allows the student to control the amount and type of help received. While the messages received are not as personalized as natural tutoring help, their content is appropriate to the context of problem solving subtasks and to the specific type of support (coaching or instruction) and type of information requested by a student. A simple natural language interface might be added eventually for entering requests to the tutor. Our priority is to test a general approach to the design of a computer tutor that can supplement effective problem-based teaching of statistics by teachers. As such, we have given greater weight to providing tutor help that provides contextually appropriate content than to attempting to simulate natural dialogue with a tutor. Emulating natural tutorial dialogue may be an important objective for future tutors, but in our view it is important that the content of tutor help accurately reflect how tutors model and explain problem-solving procedures and knowledge to students and how they provide them with guidance, coaching, and feedback.

5. Conclusions

Our analysis of expert human tutoring in statistics has shown that the tutor modeled and explained problem solving methods to students through interactive dialogue with the students in a context of problem-solving actions. This situated tutorial dialogue supports students’ individual and collaborative learning processes in many ways. The tutor organized his modeling and explanation in terms of a discourse macrostructure that corresponds to the frame structure of the procedures that are used by experts to solve problems in the domain of ANOVA. Through his discourse, the tutor provided students with access to contextual descriptions and explanations of problem solving procedures in terms of relevant conceptual, theoretical, and practical knowledge as they were being applied to understand and solve problem examples. The tutor’s explanations provided models of expert reasoning and problem solving for these practical examples, and they enabled the students to link procedures into a robust conceptual understanding of the theory and methods of ANOVA. In this way, the tutor’s modeling and explanation provided a knowledge base that could serve as a foundation for subsequent coaching to scaffold students’ development of autonomous knowledge and expertise. The tutor’s dialogue also provided knowledge that was adapted to the student's needs. The effectiveness of tutoring by experienced tutors appears to be attributable to the manner in which expert tutorial dialogue integrates conceptual and procedural knowledge so that it is adapted to students' as they learn through practice in solving authentic problem examples. Through its procedural macrostructure and the content of its explanations, the tutor's situated discourse provides students with support in developing a robust knowledge base and skill in applying this knowledge to understand and reason about new problem examples.

Networked computers provide a natural way to extend such tutor-supported problem-based learning opportunities to large groups of learners. The provision of computer coaching functions that emulate effective human tutoring is one way of ensuring that cognitive tools for learning will evolve as we move from a text-based learning paradigm to interactive problem-based conceptions of learning. The approach to tutor development we have described has the potential to provide appropriate coaching support to students who are working in problem-based learning situations. The approach is generic in the sense that it is applicable to other subject-matter domains and educational settings. Our intent is to produce a practical, research-based methodology, authoring tools, and learner environment that can enable developers to use widely available network programming tools to develop computer coaching environments that , because they emulate expert human tutoring, will be appropriate and effective in supporting collaborative and problem-based learning under natural conditions of cognitive apprenticeship.

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