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ABSTRACT

This project developed a new kind of computer simulation and explored its impact on teaching and learning in introductory biology. The aims of the project were to: (1) develop a flexible simulation environment that would permit students to design, build, and test realistic simulations; (2) support student experimentation with intelligent tutoring expert systems that could explain how particular designs met or failed to meet specific design goals; and (3) develop a student manual as a curriculum to accompany the software for use in biology laboratory sessions. Student and instructor materials were created and tested in small group protocols. It was found that some of the computer graphics and software design of the simulation components were effective even though they were more complex than traditional modeling techniques, and that existing artificial intelligence models need to be further developed before they can be used in programmed tutoring for science instruction. Videotaped protocols of pairs of students exploring the software using written directions proved to be a valuable formative evaluation techniques. (DB)

Biology Laboratory Construction Kit with Intelligent Tutor

Final Project Report

Grantee Organization:
University of Oregon
Department of Information Science
Eugene Oregon 97403

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G008730445

Project Dates:
Starting Date: September 1, 1987
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FIPSE Program Officer:
Jay Donahue

Grant Award:

Year 1:	$129,668
Year 2:	$141,887
Total:	$271,555

Summary

The project had three aims: (1) to develop a flexible simulation environment that permitted students to design, build and test realistic simulations; (2) to support student experimentation with an intelligent tutoring system that could explain how particular student constructions met or failed to met specific design objectives; and (3) to develop a student manual as a curriculum to accompany the software. This curriculum would be appropriate for use in three two-hour laboratory sessions in an introductory biology class.

The aims were met as follows: (1) Simulation software for the Apple Macintosh Computer (Mac II with 2 Mbyte RAM) was developed which permits graphical construction of a variety of cardiovascular systems from a toolkit of basic parts. (2) Expert tutoring software was developed on the Symbolics Computer and converted to the Macintosh, but not linked to the Construction Kit; and (3) Student and instructor curricular materials were created and tested in small group protocols. The Construction Kit and curriculum will be tested during the 1989-90 academic year at the University of Oregon, UC Santa Barbara, and Kalamazoo College.

A 17 minute video tape describing the project's methods and demonstrating the construction kit was created as part of this report.

Title of Project:

Biology Laboratory Construction Kit with Intelligent Tutor

Title of Products:

- Cardiovascular Construction Kit
  - Software (Beta test version)
  - Student Manual (Draft)
  - Instructor Manual (Draft)
- Cardiovascular System Tutor
  - Software (as-is prototype)
  - Documentation
    - Douglas, S.A. and Z-Y Liu. "Generating Causal Explanation from a Cardio-Vascular Simulation" In Proceedings of the International Joint Conference on Artificial Intelligence, Detroit, MI August, 1989.
    - Downing, K. "Exploiting Teleological Biases in Design Criticism" unpublished
- Project Report video tape (17 min VHS)

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Project Overview

The project had three aims: (1) to develop a flexible simulation environment that permitted students to design, build and test realistic simulations; (2) to support student experimentation with an intelligent tutoring system that could explain how particular designs met or failed to met specific design goals; and (3) to develop a student manual as a curriculum to accompany the software for use in three afternoon laboratory sessions in an introductory biology class.

The aims were met as follows: (1) Simulation software for the Apple Macintosh Computer (Mac II with 2 Mbyte RAM) was developed which permits graphical construction of a variety of cardiovascular systems from a toolkit of basic parts. (2) Expert tutoring software was developed on the Symbolics Computer and converted to the Macintosh, but not linked to the Construction Kit; and (3) Student and instructor curricular materials were created and tested in small group protocols.

A 17 minute video tape describing the projects methods and demonstrating the construction kit was created as part of this report.

Purpose

The purpose of this project was to develop a new kind of computer simulation and explore its impact on teaching and learning in introductory biology.

Background and Origins

Previous computer simulations used for instruction in biology have employed models of a single fixed biologic system. For example, FIPSE has funded the development of computer simulations in physiology for medical students (Peterson and Campbell 1985-87). Those computer programs contained detailed simulations of particular biologic systems and sub-systems, e.g., the left ventricle of the canine heart, the human lungs and chest wall. While accurate, the models were inflexible. They did not permit the broader range of topics typical in an introductory course, i.e., a survey of cardiorespiratory systems across species, phyla, or kingdoms.

Further, previous simulations did not permit students flexible opportunities to design a wide range of experiments, generate and test hypotheses, and demonstrate results.

Project Descriptions

The project had three objectives:

(1) to develop a flexible simulation environment (construction kit);

(2) to support student experimentation with an intelligent tutor;

(3) to develop a written curriculum to accompany the software.

These three components were planned for dissemination as an educational product.

Construction Kit The construction kit consists of components of a vertebrate cardiovascular system: ventricles, capillaries, and vessels with and without one-way valves and branches. In addition there are lung (oxygen source) and skeletal muscles (oxygen sinks) which can be attached to the capillaries. These components are presented in the program interface as graphic objects that are assembled by the student into a wide variety of constructions. Gauges, capable of measuring blood pressure, flow, volume, and oxygen concentrations can be attached to the components. Gauges display their data as a time-series histogram showing the current system status and a brief history leading to the current point.

Intelligent Tutor The great diversity of "organisms" that can be constructed with the kit, and the Project's curricular objective of encouraging student-directed exploration, implied that the Construction Kit would lead students to impose a heavy demand for explanations from their teachers. The Project developed a software-based tutor to help offset this demand, by providing explanations to the student. Two objectives were stated for the tutor: create a curricular framework based on the student's past work and knowledge, and explain or critique the behavior of the system created by the student.

These two objectives placed two different demands on the design of the tutoring software. Guiding the student through a set of general curricular goals required a method for modeling the student's knowledge of the system and communicating curricular objectives. For example, a general goal might be to understand that one-way valves direct blood flow in one direction. A corresponding curricular objective might be to make a circulatory system with counterclockwise flow and never any clockwise flow.

Explaining and critiquing the behavior of the system required a method for representing system behavior in terms of functional goals. Given the curricular objective above, and a student construction, the critic's task is to find differences between the objective and the current behavior and assign credit and blame for the current behavior *in terms of the curricular goal.* There are many reasons why the student's construction might have undesired clockwise flow at a given time and place. The task of the critic is to identify the reasons for that clockwise flow in terms of the functional goal (or purpose) of the system.

Written Curriculum. As part of the formative evaluation process, written directions for using the lab were developed. Students followed these directions, as they would a laboratory exercise. Videotapes of students using the instructions and simulation were made and used to revise both the software and the student tasks.

Project Results

Construction Kit: Cardiovascular simulation. The cardiovascular components in the construction kit are programmed in the computer as software "objects." Objects communicate by passing messages among themselves, e.g., the heart ask the event-clock what time it is, the clock answers with a message telling the time. The heart uses this information to determine whether or not it is in the contraction phase of its beat. Software objects, like the event-clock and the heart, allow the programmer to localize knowledge about how a particular task is accomplished. During preliminary design we were concerned that the extensive message passing between the objects would slow the program unacceptably. This did not prove to be the case. We even had sufficient reserve computational power to animate the constructions.

An unanticipated problem arose in defining "normal" and "abnormal" physical properties (i.e. heart strength, vessel diameter) for the cardiovascular components. Since the Cardiovascular Construction Kit allows the creation of arbitrary circulatory systems, the selection of nominal values for the component properties becomes arbitrary. "Normal" in the context of a human implies a very specific "construction" of the cardiovascular parts.

This problem of defining "normal" and "abnormal" was mitigated by a heavy emphasis on qualitative reasoning. Properties are described to the student in qualitative terms (high, medium, low).

Qualitative measurements created a new problem: absolute vs relative measurement. Is "High" absolutely high, or high relative to some other component or situation? Further, how can a derived property (i.e. resistance = (pressure1 - pressure2) / flow) be computed when pressures and flow cannot be quantified?

These questions have not been fully resolved. The current system provides graphical displays of data that can be read semi-qualitatively. The axes have arbitrary units, and it is possible to see, and estimate differences in pressure. Currently, our curricular goals do require students to compare relative magnitudes, but do not require them to work with computed results like resistance.

Construction Kit: Human-machine interface. We believe that the current interface is quite simple to operate and understand. We feel this is borne out by evidence in the videotape protocols and well as experience of other faculty using the program.

Development of the human-machine interface required extensive testing with students. Students brought prior knowledge and expectations about the cardiovascular system (both correct and incorrect) to the software testing sessions. These student expectations confounded interpretation of test data. The problems resulting from student knowledge and expectations were differentiated from those resulting from the software through extensive use of videotaped protocols of students working with prototype curricula.

Intelligent Tutor. The development of causal explanations for an arbitrary construction proved much more complex than we anticipated. Our goal for the tutor was to provide the student on-line explanations and coaching while they were working with the construction kit. To provide explanations, the tutor needed to "understand" and "reason about" the student's construction. We attempted to create this "understanding" within the tutor using established artificial intelligence techniques (e.g. confluences and process models). Neither of these approaches proved satisfactory. Elemental behaviors (of individual components) can be easily represented, but arbitrary aggregations of components have complex interacting behaviors.

These complex behaviors were not easily synthesized from the elemental ones using established techniques.

Introspection into ourselves as explainers, and examination of the teaching objectives of several freshman textbooks, led us to develop a tutoring system that employs teleology as a way of selecting which components and behaviors are germane to an explanation in a complex system. For example, a cardiovascular construction might have the goal (in the mind of its designer and told to the tutor) of satisfying the oxygen needs of an organ. To accomplish this, a sub-goal would be providing a flow of blood to that organ and oxygenating the blood before it reaches the organ. Each of these subgoals has other sub-goals.

From the standpoint of the tutor, each goal implies features to seek in the behavior of the student's system. For example, when critiquing a construction whose goal is to provide oxygen to an organ, the tutor would look for a flow of blood to that organ. Elements of the student's design that inhibit the flow of blood to the organ would be assigned blame for the system's failure. Note, the system may be doing something else very well, but if that something is not what the tutor is looking for as the goal (or "purpose") of the system, the design is not recognized as a success. If the student changes the goal then the same design may become a success.

Written Curriculum. The curriculum was designed as 3 two-hour laboratory periods, supported by lecture and pre- and post-laboratory discussion sections.

It is a compromise between two methods of computer-based teaching: 1) an open-ended constructionist approach and 2) a directed tutorial approach. We begin the curriculum with direct activities designed to meet specific curricular goals: acquainting the student with the model's behaviors and operation and reviewing specific domain knowledge. Lab two is less directed. By lab three we have switched to a constructionist approach. Student's are asked to pose their own questions (hypotheses) and design experiments to answer the questions. Labs One and Two model problem-posing and experimental design methods for the students.

The first laboratory validates information learned via other sources with the behavior of the simulation. For example, student's know that blood circulates in one direction and that the heart has one-way valves. A beginning task has them confirm that a simulation can be constructed to have the same properties. Students may not know the exact consequences of a missing valve in the heart, but they do know that the circulation will not perform normally. The first experiment in the laboratory has them remove a one-way valve and explore the consequences, then draw a general hypothesis about the function of one-way valves.

The second laboratory emphasizes hypothesis construction. The content goal is to develop an appreciation of the manifold issues that determine "optimal" cardiovascular performance. At the beginning of the lab, students are "walked" through four steps in an experimental process:

(1) Selection of a hypothesis
(2) Designing an experimental cardiovascular construction.
(3) Data collection and analysis
(4) Presentation of a conclusion

As the lab progresses they are given less tutorial assistance. The second problem requires the students to draw their own conclusions. In the third students must perform the data collection, analysis and conclusion. The fourth problem in this lab provides only a hypothesis.

The third laboratory is presented as a "game." Teams of students are to each build a cardiovascular system with the goal of maximizing, or minimizing, some feature(s) of its performance. One team might be assigned to build with two hearts, another only one heart but provided extra lungs.

Summary and Conclusions

Construction Kit: Cardiovascular simulation. Object-oriented design of the simulation components proved more complex than traditional modeling techniques. In traditional mathematical modelling all the equations for a model are stored in one place and evaluated in a known sequence by a single computational process. Object-oriented modelling distributes the relevant equations among independently acting objects. In this project, each cardiovascular component is a software object that contains its own mathematical representation. While the object-oriented modeling approach was more complicated than anticipated, it was quite feasible and produced a very effective simulation environment.

Construction Kit: Human-machine interface. The Apple Macintosh, programmed in object-oriented LISP proved an effective solution to designing and developing an easily used human-machine interface.

Intelligent Tutor. The development of causal explanations for an arbitrary construction proved much more complex than we anticipated. While we find much to recommend further development of intelligent tutors for aids in scientific laboratories, the open-ended, constructive nature of the modelling in this Project proved too much for a tutor using existing AI techniques. We are, however, well along in the process of developing better tutoring techniques.

Written Curriculum. The development of the curriculum concurrently with the simulation provided valuable input the the software design. However, the details of curricular design did not progress rapidly until the very last months of the project when the software was stable and its human interface robust. Consequently, there was no opportunity within the scope of the project to develop a consensus among instructors at different schools about curricular objectives or their implementation in the construction kit or student materials. The project would have benefitted from an additional year, devoted mostly to writing and especially classroom testing of the curriculum. It also seems that our evaluation would be have been enhanced by testing with several instructors and several schools. As of this writing, September 1989, UC Santa Barbara, Southern Illinois University, and Kalamazoo College have expressed interest in testing and evaluating the software and student materials.

Formative Evaluation via Videotape. Videotaped protocols of pairs of students exploring the software using written directions was a very valuable formative evaluation technique. It was useful for diverse assessments including: software interface, instructional design, and underlying student knowledge, abilities, and misconceptions. We tried several protocol formats, including taped interviews between a student and a member of the project staff, a student working alone, and teams of two students exploring independently. Teams were the most successful. Further, we developed the impression that same-sex teams were more successful than mixed sex teams and also that female teams were more cooperative and nonjudgmental than male teams. These observations, however, are anecdotal, and may not hold for other age groups or tasks.

Appendices

Construction Kit Software

(2 Macintosh Disks - Required 2 MByte RAM)

Videotape report (VHS format)

Draft Student and Faculty materials

Two Articles

Douglas, S.A. and Z-Y Liu. "Generating Causal Explanation from a Cardio-Vascular Simulation" In Proceedings of the International Joint Conference on Artificial Intelligence, Detroit, MI August, 1989.

Downing, K. "Exploiting Teleological Biases in Design Criticism" unpublished