Exploratory learning with a computer simulation for control theory : learning processes and instruction support

Citation for published version (APA):
Njoo, M. K. H., & Jong, de, T. (1993). Exploratory learning with a computer simulation for control theory : learning processes and instruction support. *Journal of Research in Science Teaching*, *30*(8), 821-844. https://doi.org/10.1002/tea.3660300803

DOI:
10.1002/tea.3660300803

Document status and date:
Published: 01/01/1993

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 22. Aug. 2022

JOURNAL OF RESEARCH IN SCIENCE TEACHING VOL. 30, NO. 8, PP. 821–844 (1993)

Exploratory Learning with a Computer Simulation for Control Theory: Learning Processes and Instructional Support

Melanie Njoo* and Ton de Jong

Department of Philosophy and Social Sciences, Eindhoven University of Technology, Den Dolech 2, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Abstract

Computer simulations create a context that is well fitted for exploratory or discovery learning. The aim of the present two studies was to gain deeper insight into what constitutes exploratory learning and to assess the effects of a number of instructional support measures. The domain involved was control theory at the university level. In the first study we made an inventory of exploratory learning processes by observing 17 students working with a computer simulation and analyzing students' thinking-aloud protocols. Subjects received a structured assignment with hints as an instructional support measure. In the second study, 91 students received an open-ended assignment with instructional support that consisted of an information sheet and a set of fill-in forms. On both sheets and forms, six cells were presented. A cell was given for each of the following six learning processes: identifying variables and parameters, generating hypotheses, designing an experiment, predicting, interpreting data, and drawing of conclusions. Information sheets were either of a domain specific or of a general nature. The set of fill-in forms were either free or had the cell HYPOTHESIS already filled in. The statements of the students on the fill-in forms were analyzed in a stepwise order. Twenty-two detailed learning processes were identified and classified. Two of the main classes of processes are transformative and regulative. Both studies showed that students were reluctant to apply learning processes that are considered characteristic for exploratory learning. Furthermore, students had problems with the exploratory learning processes, especially with the processes of generating hypotheses, interpreting data, and drawing conclusions. Effects of the instructional support measures were not conclusive. Hints did not result in significant improvements of the study process. Supporting learning processes with information sheets appeared to help students in performing learning processes, but no different effects of domain specific and general information could be found. Students who were provided with hypotheses showed a higher global activity level and higher scores in domain correctness of their learning processes.

Contemporary learning theories describe the learner as an active agent of knowledge acquisition. *Exploratory* or *discovery learning* is an instructional and learning approach that is well in line with this general notion. With exploratory learning information is not given to learners in an expository way but an open learning environment is offered in which learners have to formulate themselves: principles, procedures, or higher order skills. By means of inquiry,

---

* To whom requests for reprints should be sent, at BSO/Instruction Technology BV, Oude Utrechtseweg 26-30, P.O. Box 543, 3740 AM Baarn, The Netherlands.

Published by John Wiley & Sons, Inc. CCC 0022-4308/93/080821-24

scientific discovery, problem solving, inductive reasoning, and so forth, learners have to acquire their knowledge in an active, constructive way.

Exploratory learning is seen as important because of two reasons. First, it is assumed that the domain at hand may be learned in a better or deeper way because it would encourage meaningful incorporation of information into the learner's cognitive structure. Secondly, knowledge of exploratory processes itself is seen as an important skill. This notion has recently received renewed attention through the introduction of *computer simulations* as an instructional device. Computer simulations are well fit for exploratory learning because they can hide a model that has to be discovered by the learner.

However, studies on discovery learning and exploratory learning with computer simulations in particular, quite often do not report straightforward successful results (Swanson, 1990; Veenman & Elshout, 1990). There can be two possible grounds for unsuccessful use of computer simulations as an instructional device. First, exploratory learning processes are too difficult for learners and because of that they make mistakes and show inefficient and ineffective behavior. Secondly, learners are not as active as we assume and despite the fact that they have exploratory skills they do not use them.

Improvement in exploratory learning might be accomplished by supporting the learning processes at the moment learners apply them or stimulating learners to engage in exploratory learning. Recently a number of systems that incorporate a simulation as well as additional instructional measures have emerged (Shute & Glaser, 1990; Towne et al., 1990; White & Frederiksen, 1990). In analyzing these instructional measures (see also van Berkum & de Jong, 1991; de Hoog, de Jong, & de Vries, 1991) we recognize three seemingly contradictions. First, it seems obvious that learners should be restricted in what they are allowed to do in order to prevent them from floundering. Examples of such restrictions are providing the learner with increasingly complex models (White & Frederiksen, 1990) or prohibiting learners from entering specified values for some variables (Böcker, Herczeg, & Herczeg, 1989). On the other hand learners need some kind of encouragement by stimulating them to perform exploratory actions (e.g., by means of a Socratic dialogue, Finegold & Gorsky, 1989). Second, a number of studies recommend directing the learner in a certain way. This could be done by giving specific feedback on which variable to manipulate next (e.g., Towne et al., 1990). On the other hand we consider learner control of paramount importance to exploratory learning. From this perspective we should design supportive measures that leave as much freedom to the learner as possible. Examples of such nondirective support are learner instruments such as hypotheses scratchpads (van Joolingen & de Jong, 1991a,b). Third, instructional measures can be imposed upon learners (*obligatory measures*) whereas a different approach could be to leave the control over use of instructional measures in the hands of the learner (*nonobligatory measures*). Adequate support needs to be balanced between the extremes.

For the development of adequate instructional measures for computer simulations studies are needed that identify the learning processes involved in exploratory learning. An example of an experimental study that looked directly at exploratory or scientific discovery learning is the one by Klahr and Dunbar (1988). Their fundamental assumption is that scientific reasoning requires search in a *hypothesis space,* which is the space that represents all the possible hypotheses, and in an *experiment space,* which is the space that represents all the experiments that can be conducted. In their group of subjects they distinguished theorists who prefer to search the hypothesis space and conduct experiments to test the current hypothesis, and experimenters who tend to conduct experiments without an explicit hypothesis.

Whereas Klahr and Dunbar (1988) used a simple task domain there are a few studies that have looked at the exploratory study process in semantically rich domains (e.g., Camacho & Good, 1989; Reimann, 1989; Rivers & Vockell, 1987; Shute 1990; Shute & Glaser, 1990). Most of these studies focus on scientific discovery or scientific problem solving in general whereas others focus on specific aspects. For instance, Lavoie and Good (1988) emphasize prediction behaviors and Reimann (1989) emphasizes hypothesis generation. What we need, however, is detailed and complete knowledge of exploratory learning in order to estimate potential problems in this process and to design effective support measures. In this respect we will use the term *learning process* for indicating specific mental actions of learners and the terms *study process* for the complete knowledge acquisition process.

Two studies will be described in this article that together have two aims. The first aim is to gain a deeper understanding of the learning processes that constitute exploratory learning. The domain involved in the studies (control theory) is rather complex, has a number of specific (dynamic) key concepts, and provides clear experimentation possibilities. In this respect it represents a domain that is specifically appropriate for exploratory learning with a simulation. The second aim is to examine the effects of different forms of (off-line) instructional support on quantity and quality of these learning processes. The instructional support consisted of hints in a guided assignment, learning processes support through fill-in forms that divided the study process in separate learning processes, and information sheets that contained either general and/or domain specific information on the learning processes, and providing learners with hypotheses to explore.

Educational Context

The domain involved in these studies is a subdomain of mechanical engineering: control theory. Key concepts in the domain are: Laplace transform fundamentals, frequency domain analysis, and time domain characteristics. The subject is taught as a second year course at Eindhoven University of Technology. The primary goal of the course is to teach students how to regulate models of mechanical systems by means of a control devise of which they can alter the control law (e.g., proportional or integral). The purpose of the regulation is to obtain an optimal functioning of the system where optimal is described by preferences of the students, some prescribed or mechanical requirements (e.g., offset), or the properties of the system (e.g., stability or damping). Students work with a simulation program called PCMatlab (©Mathworks). Originally PCMatlab was not developed for educational purposes but is intended for scientific and engineering numerical calculations and graphics. PCMatlab offers the student a range of standard functions. Input consists of differential equations that represent specifications of the system and the control law. The output consists of graphs that describe the relations between input and output signal or numerical data that represent the feedback of the control.

PCMatlab is used in the educational setting of a computer lab, given parallel to lectures. The lectures offer the theoretical background of control theory. The computer lab consists of one session (3.5 hours) a week for a period of 4 weeks. During the computer lab, students work in fixed pairs and are free in the choice of their partner. Usually about 10 to 15 pairs are working in a classroom at the same time with two tutors available. In the lab students receive assignments that are meant as an exercise, offering a model to explore, study questions, and problems to solve. The assignments are not designed specifically to stimulate exploratory behavior. Students have to hand in a written report that is discussed with their teacher.

Study 1: Charting Learning Processes and the Effect of Giving Hints

The aim of the first study was twofold. First, to create a list of exploratory learning processes and, second, to evaluate the effects of providing the learners with stimulating hints on the use of specific learning processes. The main reason for introducing the hints was because in a previous study (Njoo & de Jong, 1991) subjects did not behave as explorers and were reluctant to use specific exploratory learning processes.

Experimental Set-up and Techniques

Subjects and Procedure. Subjects in the study were 17 students working in pairs. The eight pairs (one "pair" consisted of 3 students) of subjects were selected at random. Subjects were assigned to one of the two experimental conditions on the basis of the average score on three prior, introductory, courses. We distinguished good (scores higher than 70%) and poor pairs. These groups were evenly assigned to the two conditions.

The experiment was conducted as part of the normal curriculum. Subjects did not work in the normal computer room but pairs of subjects worked together in separate rooms. The tutor was waiting in another room and was called whenever the subjects asked for assistance. In this way, the verbalizations could not influence the tutor's actions. Moreover, subjects were now urged to try to solve their problems themselves.

Experimental Conditions. Half of the subjects received the original assignment (unguided condition), the other half received an altered assignment (guided condition). The alterations within the assignment were aimed at stimulating an exploratory attitude, by giving suggestions for performing the learning processes hypotheses generation and testing (see Appendix A for a more precise description of these processes). For example,

unguided group:	What is the reaction of the system on a step in u(t)?
guided group:	What is the relation between the step response and the location of the poles? Make a prediction of the reaction of the system to a step in u(t); verify your prediction. Justify your answers.

The suggestions may seem quite straightforward, but the style of questioning in the original assignment was very direct. For the guided version, we choose to alter the assignment on the aspect of content and not on the aspect of style.

Our expectation was that, as a result of the altered assignment, the guided group would show a higher use of the learning processes hypothesis generation and testing.

Data Collection. Thinking-aloud protocols were used as the main technique for determining the learning processes. Furthermore, for sustaining this analysis we used log-files (on-line registrations of subjects' input and program output), the notes subjects made, and the notes we asked the tutor to make about his idea of the subjects' problem.

The protocols of the subjects were transcribed and analyzed in cooperation with a domain expert to make sure that domain-related reflections of the students would be properly interpreted and analyzed. The same method, which was used in Ferguson-Hessler and de Jong (1990), showed a high (convergent) validity. A similar approach was applied by de Jong and Ferguson-Hessler (1991) and an interrater reliability of 88% was achieved. We used a pair of subjects as the unit of analysis. It was impossible to discriminate between the subjects' line of thought.

Results

Overview of Exploratory Learning Processes. The protocols gathered in this study together with results from the literature (e.g., Klahr & Dunbar, 1988; Lodewijks, 1985; Njoo & de Jong, 1991; Reimann, 1989; Rivers & Vockell, 1987) served as the basis for developing an overview of exploratory learning processes. At the highest level we categorized exploratory learning processes into four classes: transformative, regulative, operating the simulation, and general.

Transformative processes can be characterized as processes of scientific inquiry and classified into four main categories: analysis, hypothesis generation, testing, and evaluation. These processes were subdivided into more detailed processes. For example, in the category testing, processes for making predictions and data interpretation were included. These latter processes can also be subdivided. *Regulative processes* refer to the executive control of the study process (e.g., planning, monitoring). *Operating the simulation* is concerned with the user interface of the simulation program. The last class contain processes of a *general* nature (e.g., calculating). The complete list of 22 processes is given in Appendix A. In order to give a complete overview the list contains both processes and activities.

A Comparison of Exploratory Behavior for the Guided and Unguided Groups. Once developed, the overview of learning processes was used as an analysis scheme for assessing the thinking-aloud protocols of the subjects. For reasons of efficiency we had chosen three parts of the assignment for analysis. We expected that the selected parts would most likely involve most of the explorations of the subjects. The parts of the assignment that were left out consisted of necessary but rather monotonous activities (preparations for the design of the model and regulation). Table 1 gives the mean percentages for the guided and the unguided groups. The processes as depicted in Table 1 are the processes from the most detailed level from Appendix A. One of the most important findings is that t tests showed no significant differences between the guided and the unguided groups with $p < .05$. Our introduction of hints clearly failed to stimulate true exploratory behavior. Learning processes paramount to exploration (such as hypothesis generation, designing an experiment, manipulating variables) were (almost) absent. This is in line with previous results (Njoo & de Jong, 1991). We also saw that the subjects' need for extra (domain) information was quite high (about 12%).

The number of planning processes was quite high (especially if we compare this to a nonexploratory environment as learning with text [de Jong & Njoo, 1992]). However, subjects tended to plan at short notice instead of overall strategic planning. Planning mostly related to the general processes such as supportive processes for interpretation and calculating. A remarkable high percentage was found for the monitoring process (about 17%). However, the monitoring process quite frequently consisted of (re)reading the assignment.

The general conclusion from this study is that providing the learners with hints was not sufficient for stimulating them in applying exploratory learning processes. Therefore, in Study 2 we examined different instructional measures.

Study 2: Supporting Learning Processes and the Effect of Providing Hypotheses

Compared to Study 1, the experimental groups in Study 2 were given an assignment that required more initiative and free activity. Moreover, in order to stimulate and support the subjects, they were given instructional support for specific exploratory learning processes. Support consisted of fill-in forms and information sheets.

Table 1
*Mean (*M*) and Standard Deviation (*SD*) of the Percentages of Learning Processes for the Unguided and Guided Groups*

		Group			
		Unguided (*n* = 4)		Guided (*n* = 4)	
	Process	*M*	*SD*	*M*	*SD*
1	Looking for/finding information	11.8	5.4	12.8	2.2
2	Model exploration: identifying	0.8	1.7	1.1	0.9
3	Model exploration (qualitative)	3.4	4.3	3.0	1.9
4	Model exploration (quantitative)	0	0	0.3	0.7
5	Hypothesis generation	0	0	0	0
6	Design an experiment	0	0	0	0
7	Qualitative prediction	1.6	1.3	0.6	0.7
8	Quantitative prediction	0.4	0.8	0	0
9	Manipulation of variables/ internal parameters	0	0	0	0
10	Manipulation of external parameters	0	0	0	0
11	Local output interpretation	10.1	2.7	6.2	0.8
12	Conceptual output interpretation	4.9	1.6	2.7	1.9
13	Supportive processes	1.9	0.7	2.5	2.4
14	Evaluating/judging	6.6	2.9	7.9	2.1
15	Generalizing	0.4	0.8	0.2	0.4
16	Planning	12.7	5.0	11.2	3.5
17	Verifying	3.5	1.8	3.5	2.1
18	Monitoring	16.2	1.4	19.3	4.1
19	PCMatlab operations	13.5	3.4	9.9	1.3
20	Calculating	3.9	1.5	6.2	2.9
21	Making notes	6.1	2.4	7.9	1.8
22	Off-task	2.4	3.1	4.9	2.7

Note. The percentages are the absolute number of each learning process related to the total number of learning processes applied by each pair of subjects. The total number of learning processes applied by each pair of subjects differed from 61 to 122, with an average of 84.5.

Experimental Set-up and Techniques

Subjects and General Procedure. Subjects in Study 2 were 91 mechanical engineering students. Subjects worked in pairs and this resulted in 44 pairs (some "pairs" consisted of three students). Four experimental groups (*n* is 7 to 10 pairs of subjects) and a control group of 10 pairs participated. The control group followed the simulation lab with a directed assignment like the ones used in Study 1 and no additional support. All subjects in the experimental groups received:

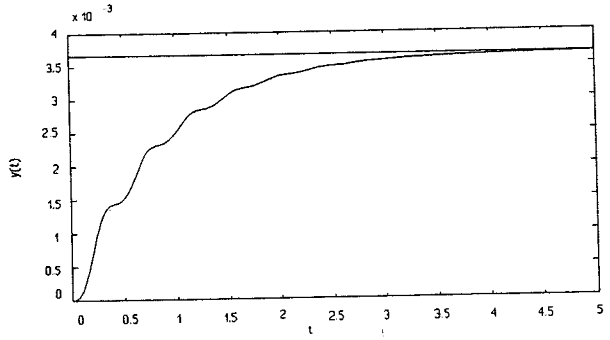
1. Specifications of a modeled system (a ship that had to be kept on course).
2. An open-ended assignment to explore the modeled system with the aim of constructing

the optimal regulation for the system. It was stressed to the subjects that this assignment was different from other assignments they had received in the lab until then and that they were free to explore the system as they wanted. It was also emphasized that their explorations did not necessarily have to involve the optimal regulation but could also involve less optimal regulations. We informed them that the explorations of other (nonoptimal) regulations could result in more insight in the system and regulation in general and that this insight could help them to explain their final choice.

3. Additional support in the form of an information sheet and fill-in forms. Different variations of the information sheet and fill-in forms were designed. Experimental groups differed in the specific variation they received (see the next section).

All groups made a posttest that consisted of seven multiple-choice questions that tested qualitative insight in the domain. An example of a test item is given in Figure 1.

Experimental Conditions. The additional support in the experimental groups was given off-line (paper and pencil) and it consisted of an information sheet and fill-in forms. An information sheet was offered to the subjects at the start of the lab session. This sheet contained information on a number of exploratory learning processes. After having read the information sheet subjects



Above the step response of a third order system is given.

The system has:

a) one dominant pole on the real axis and furthermore two mutually conjugated poles, all in the left half plain.

b) at least one pole in the left half plain.

c) three real poles in the left half plain.

Figure 1. Test item of the posttest.

were asked to work with the simulation using the fill-in forms. Fill-in forms offered the learners the opportunity to note down their thoughts, actions, or results of the simulation for each of the exploratory learning processes that were explained on the information sheet.

The structure of both information sheets and fill-in forms was identical: The sheets and forms were divided into six cells labeled VARIABLES & PARAMETERS, HYPOTHESIS, EXPERIMENT, PREDICTION, DATA INTERPRETATION, and CONCLUSION. The size was 16.5 × 11.8 in. (42 × 30 cm).

The cells of the information sheet contained information on the six exploratory learning processes. We designed two variations of the information sheet. In one variation we only offered general information about the six learning processes. In the other one, learners were not only provided with this general information, but additionally with domain-specific information on the processes.

Two examples will clarify this difference. The examples are from the cell VARIABLES & PARAMETERS. The first example is a part of the general version of this cell:

> A model is described by variables and parameters. Variables represent the state of the system and can be classified as dependent and independent variables. The independent variables are not influenced by other variables in the model.

The second example is a part of the domain-specific information given in this cell:

> The independent variables could be: the time t; the input signal alpha(t) and its Laplace transformation A(s); . . .

The set of fill-in forms came in two variations:

1. Forms that had only blank cells with the six labels (free fill-in forms).
2. Forms that had the cell HYPOTHESIS already filled in (hypotheses fill-in forms). Each pair of subjects received nine fill-in forms, so there were nine different hypotheses already given. Subjects in this group were also allowed to generate other hypotheses. For doing this they received a few free fill-in forms. The hypotheses that we offered to the subjects gave different viewpoints on the model and the different possible regulations for the system. The hypotheses were stated in an affirmative or a negative sense, could be verified or falsified, and differed in complexity. Two examples of hypotheses that we provided are:

> With a proportional control law you do not have influence on the stability of the system. The value of the feedback amplification K has influence on the sub or super critical damping of the system.

The two experimental conditions we created were information sheets (general or domain specific) and fill-in forms (free or hypothesis). Combining these conditions resulted in the following four experimental groups:

1. General—Free (n = 7 pairs);
2. General—Hypotheses (n = 10 pairs);

3. Domain specific—Free ($n = 8$ pairs);
4. Domain specific—Hypotheses ($n = 9$ pairs).

The experimental groups (that were existing computer lab groups) were assigned to the conditions at a random basis. Subjects were instructed to read the information sheet carefully and to work through the assignment by filling in forms from the set of fill-in forms. There was no compulsory order of cells and subjects were urged to follow the order they preferred.

Data Collection and Analysis. For assessing the effects of the different instructional support measures on the exploratory study process we analyzed the statement that the subjects noted on the fill-in forms. The analysis was performed in a stepwise order by introducing a number of levels for the analysis. At each level a specific characteristic of the statements was assessed. Some of these characteristics are based on the "learning indicators" of Shute and Glaser (1990).

The first level is the *global activity level,* which is an assessment of the general activity level of the subjects. Global activity level is defined by the number of forms and the total number of cells filled in. The second level is the *learning process validity* level, which is an assessment of aspects of the statements given by the subjects in each cell. The aspects were related to general description of the cell as was given on the information sheets. At the third level we determined the *domain correctness* of the aspects of the statements that had proven to be learning process valid at the previous level. The fourth level was labeled the *consistency* level and was an assessment of the relations between contents of different cells on one fill-in form. The final and fifth level was called the *overall strategy* level and was an assessment of the development of the statements in the same cell through different forms.

The general idea behind the different levels of analysis was that each level would work as a sieve; statements (or aspects of statements) that were not valid at a certain level would not be analyzed at a next level. At each level the qualitative assessment of the subjects' statements was summarized into a quantitative score (explained below). Because these scores on each level are related to the scores on the previous level we have used relative scores. For example, scores on the learning process validity level are related to the maximum score the subjects could have achieved, given the number of cells they have used (and which was scored on the previous global activity level).

Results

Global Activity Level. At the first level of analysis the number of forms and the number of cells that were filled in were scored as an indication of the activity level of the subjects. For each pair of subjects the number of cells filled in was related to the maximum number of cells they could have filled in taking into account the number of forms this pair had used. In this way we calculated a percentage of cells filled in. In this, we have taken into account that the groups with hypotheses fill-in forms could not fill in the HYPOTHESIS cell.

Table 2 shows that overall the subjects used an average of almost five fill-in forms. Table 3 shows that almost 85% of the cells on the forms were used. On each form the subjects used an average of about 4.5 cells (the groups with the hypotheses forms could fill in only five cells).

There was a strong main effect of the type of fill-in form on the total number of forms used. The groups with hypotheses fill-in forms used an average of 5.5 forms and the groups with free fill-in forms 3.7 forms [$F(1, 30) = 15.89, p < .01$]. The type of information sheet (general or

Table 2
Mean Scores for the Number of Forms Used
(Standard Deviation in Parentheses)

Information sheet	Fill-in forms		Total
	Free	Hypotheses	
General	3.7 (1.3)	5.2 (1.1)	4.6 (1.4)
Domain specific	3.6 (0.9)	5.8 (1.8)	4.8 (1.8)
Total	3.7 (1.1)	5.5 (1.5)	4.7 (1.6)

domain-specific) had no effect on the number of forms used. The higher activity level for the groups with hypotheses fill-in forms was also found in the number of cells filled in on the forms. The groups with hypothesis forms used an average of 89.5% of the cells and the groups with free forms used 78.7% [$F(1, 30) = 5.31, p < .05$]. The groups with hypotheses forms did not make use of the possibility to use free fill-in forms to design extra experiments or to generate and test their own hypotheses. Only one pair of subjects from the General—Hypotheses group used a free form to design an extra experiment. It appeared that the hypotheses forms stimulate global activity within the framework offered but did not stimulate free activity.

Learning Process Validity. At the second level of analysis the statements given by the subjects were assessed on their learning process validity, that is, it was evaluated whether the statement in each cell answered the general description of the cell as it was given on the information sheet. For each cell we determined what aspects should be present. For example, in the cell EXPERIMENT subjects should note down the input variables, the output variables, and the values of the input variables. For the six different cells together, a total of 20 aspects was stated. To illustrate the scoring process for learning process validity, Appendix B gives a concrete example of the assessment of statements as were given by a pair of subjects on one of their fill-in forms. The learning process validity scores were calculated first by counting the number of aspects from the assessment scheme that were included in the statements of the subjects and then relating this score to the maximum the subjects could have scored given the number of cells they used. For example, if one pair of subjects used four PREDICTION cells but only had two valid predictions, they scored 50% on this learning process (prediction only has one aspect).

Table 3
Mean Percentages of Cells Filled in
(Standard Deviation in Parentheses)

Information sheet	Fill-in forms		Total
	Free	Hypotheses	
General	79.7 (21.7)	86.7 (12.9)	83.8 (16.8)
Domain specific	77.8 (11.1)	92.6 (7.8)	85.6 (11.9)
Total	78.7 (16.3)	89.5 (10.9)	84.7 (14.4)

Table 4 gives the learning process validity scores for each of the main experimental conditions separately. Thus, each pair of subjects' scores are included in the figures from Table 4 twice. It shows that overall the learning process validity score of the subjects was about 42%. The cells VARIABLES & PARAMETERS, EXPERIMENT, and PREDICTION scored 55.4%, 57.2%, and 57%, respectively. The cells DATA INTERPRETATION and CONCLUSION scored 24.5% and 25.3%, respectively. These data seem to indicate that subjects had difficulties with the learning processes data interpretation and conclusion. For the cell DATA INTERPRETATION this could have been caused by the fact that two aspects that we used as criteria for assessing the learning process validity level of data interpretation were hardly used by the subjects (comparison with other graphs/data and discussion about the experiment). For the cell CONCLUSION the low learning process validity score was mainly caused by the fact that subjects hardly generalized their findings to other models. Especially the groups with the free fill-in forms failed to draw conclusions about the validity of the hypotheses.

The only significant influence of the experimental variations on the learning process validity scores was found for the cell CONCLUSION. Both the factor information sheet [$F(1, 30) = 14.09$, $p < .01$] and fill-in form [$F(1, 30) = 27.20$, $p < .01$] had a significant effect in this cell. Table 4 shows that the groups with hypotheses forms reached 30.5% of their maximum scores whereas the groups with free forms reached 18.8% of their maximum scores. Because the former group was provided with learning process valid hypotheses they could possibly more easily review these hypotheses in the conclusion. The groups with domain specific sheets scored 29.3% in the cell CONCLUSION and the groups with general information sheets 21.4%. We expected that the domain specific information was helpful for the exploratory learning processes but we did not expect an effect for conclusions only. The group Domain specific—Hypotheses gained a high score compared to the other experimental groups on three of the six cells, namely EXPERIMENT (65.8% *SD* = 13.2), DATA INTERPRETATION (25.6% *SD* = 6.9), and CONCLUSION (33.1% *SD* = 6.8).

A comparison between the scores of the cell HYPOTHESIS is only possible for the groups that did not receive hypotheses to explore. The General—Free group only stated one learning

Table 4
Mean Scores (M) *and Standard Deviations* (SD) *of the Learning Process Validity Score for the Two Support Conditions*

	Information sheet				Fill-in forms			
	Domain specific (n = 17)		General (n = 17)		Hypotheses (n = 19)		Free (n = 15)	
Cell	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
VAR&PAR	58.2	12.3	52.6	14.0	53.6	13.1	57.7	13.6
EXPERIMENT	56.2	19.2	58.3	24.5	62.5	20.8	50.5	21.6
PREDICTION	54.1	34.8	60.0	31.6	65.5	22.7	46.2	40.7
DATA INT.	24.3	7.1	24.6	16.3	25.3	7.6	23.4	16.8
CONCLUSION	29.3	6.4	21.4	11.4	30.5	6.0	18.8	10.3
Total[a]	41.8	5.2	41.9	9.4	42.0	5.6	41.8	9.6

Note. VAR&PAR = variables and parameters; DATA INT. = data interpretation.
[a] The total learning process validity is not an average of the scores of the five/six cells. For this score the total absolute score of all cells over all forms is taken and related to the maximum score (given the cells).

process valid hypothesis and this resulted in a learning process validity score of 2.9%. The Domain specific—Free group generated seven hypotheses and this resulted in a score of 31.3%. Instead of hypotheses subjects noted down other statements in this cell such as:

1. Statements that could be scored under the description of another cell such as VARIABLES & PARAMETERS, PREDICTION, and EXPERIMENT.
2. Statements that could not be scored at this level (not relevant, not interpretable).
3. Statements that expressed a general notion or idea but did not apply to the definition of a hypothesis. These statements can be considered as general inquiries of the model. These general model explorations were meant to observe the behavior of the system without any experimental manipulations. For example: "What is the course deviation over a period of time."

Also, it appeared that subjects sometimes mingled the statements of the HYPOTHESIS and PREDICTION cells. The groups with the free forms gave eight of these mingled statements; four in the cell HYPOTHESIS and four in the cell PREDICTION. The groups with the hypotheses forms made seven of these statements in the cell PREDICTION. An example of a statement that is a mixture of a hypothesis and a prediction is: "Relative damping of the system is small because the poles are $s = -2 \times 10^{-4}$." The concept of damping does not imply a choice of experiment, such as determining the poles of the system. This part of the statement applies to a large number of experiments and can be regarded as part of a hypothesis. On the condition side of the statement the poles are mentioned. A statement about the poles implies that a specific choice has been made for a particular experiment. This part of the statement is therefore not a more general statement as would be expected of a hypothesis, but a statement of the output of a specific experiment and as such a part of a prediction.

The data as presented so far assessed statements made in a specific cell. However, it happened that subjects obviously placed statements in the wrong cell. For example, experiments were sometimes stated in the cell DATA INTERPRETATION. When we use this new way of scoring, the total learning process validity of all groups increases from 44.6% to 49.3% (*SD* = 7.4) and all cells show a (logical) higher score. The trend in scores, however, stayed equal.

Of all the statements that were placed in a wrong cell, those statements that were concerned with experiments and data interpretations were notable. Experiments were often placed in the cell DATA INTERPRETATION or HYPOTHESIS. Data interpretations were also placed in other cells, especially if subjects made use of the poles as an experiment. Statements that are concerned with the system or the relations within the system were also frequently placed in other cells. These statements had to be noted down in the cell VARIABLES & PARAMETERS but were often found in the cell HYPOTHESIS. This was especially the case in the groups with free fill-in forms.

Domain Correctness. For domain correctness we only analyzed aspects of the statements that were valid at the learning process validity level. If a subject made a mistake in one of the cells that caused mistakes in other cells, then the mistake was only scored once. Of course, subjects could state false (in the sense of hypotheses that cannot be verified) hypotheses and, therefore, the HYPOTHESIS cell was analyzed separately from the other data. Domain correctness scores were related to the scores of the previous level (learning process validity). For example, if a pair of subjects had two valid experiments, but one of them was incorrect, they scored 50% on domain correctness.

It showed that overall there is a high score on domain correctness (80.4%) of the aspects of the learning process valid statements. So, once the subjects made statements that were valid as an exploratory learning process, these statements were mostly correct at a domain level. The trend that we observed at the previous level, in which the cells DATA INTERPRETATION and CONCLUSION scored lower than the other cells, was not seen at the domain correctness level. All the cells have percentages from 70% to 85%. Again we saw significant effects from the experimental condition fill-in form on the scores in the cell CONCLUSION indicating that the subjects who had received hypotheses scored higher [$F(1, 30) = 11.52, p < .01$]. Table 5 also shows that for the total scores for domain correctness there is a similar effect [$F(1, 30) = 6.10, p < .025$]. Contrary to what might have been expected we found that providing subjects with domain-specific information did not show an effect. However, similar to most of the scores on the previous levels, the group Domain specific—Hypothesis had the highest score on all the cells (scores ranged from 86.6% to 95.4%).

Because subjects stated little hypotheses, we looked at the absolute numbers for this cell. The hypothesis that was generated by the General—Free group was domain correct. The seven hypotheses of the Domain specific—Free group that were learning process valid, were almost all correct; just one was domain incorrect.

Consistency. At the fourth level we assessed the relations between the statements in different cells on one fill-in form. We analyzed the relations: HYPOTHESIS—EXPERIMENT, EXPERIMENT—PREDICTION, EXPERIMENT—DATA INTERPRETATION, PREDICTION—DATA INTERPRETATION, and DATA INTERPRETATION—CONCLUSION. We only analyzed statements that were valid at the learning process validity level and domain correct. At the domain correctness level we assessed aspects (of statements) that were learning process valid. At this level we looked at a number of crucial aspects and if these were learning process valid we included the complete statement in the consistency analy-

Table 5

*Mean Scores (*M*) and Standard Deviations (*SD*) of the Domain Correctness Score for the Two Support Conditions*

	Information sheet				Fill-in forms			
	Domain specific (n = 17)		General (n = 17)		Hypotheses (n = 19)		Free (n = 15)	
Cell	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
VAR&PAR	85.6	18.6	73.2	22.6	84.5	17.4	73.0	24.4
EXPERIMENT	83.8	24.0	86.6	16.0	90.8	12.7	78.1	25.5
PREDICTION	72.5	39.1	68.1	41.9	78.5	32.3	60.0	47.1
DATA INT.	84.2	20.0	63.2	30.6	77.3	20.9	69.2	34.5
CONCLUSION	85.8	21.2	69.9	37.8	91.1	14.3	61.1	38.7
Total[a]	83.1	13.4	77.6	11.6	84.5	10.4	75.2	13.7

Note. VAR&PAR = variables and parameters; DATA INT. = data interpretation.

[a] The total domain correctness is not an average of the relative scores of the five cells. For this score the total absolute score over all cells and forms is taken and related to the scores of the previous level.

sis. For the cell HYPOTHESIS we also analyzed hypotheses that were scored domain incorrect because they could be falsified. Again, consistency scores were relative scores (percentages). The scores were related to the maximum possible score a pair of subjects could get. For example, if subjects had given all the necessary aspects in all the cells and made no domain mistakes, they could score all five relations. If half of these relations were correct they would receive a score of 50%.

The data show that in total 90.1% (*SD* = 24.1) of the relations given by all the subjects together were correct. It appears that learning process valid and domain correct statements result very often in correct relations. We did not find any effects of the fill-in forms or information sheets ($p < .05$). Again, the group Domain specific—Hypotheses gained high scores.

For the groups with hypotheses forms (so hypotheses were already present) we separately looked at the relation HYPOTHESIS—EXPERIMENT. Seventy-one of these relations could be analyzed and we found that only five were incorrect. It appeared that if hypotheses were provided, then the design of a matching experiment was not too difficult. However, the relation at this general level does not say anything about the appropriateness of the experiment.

Overall Strategy. As a final analysis level we assessed the development of the successive hypotheses and the relation between a hypothesis and the conclusion on the previous form. As we mentioned in the preceding section, very few statements passed the sieve. Therefore, we will only discuss some examples.

Only a few hypotheses were generated and they usually did not follow one another. In three cases the hypotheses were successive. One time the transition was from a hypothesis about the system without a control law to a hypothesis about the system with a control law. The other two cases were concerned with hypotheses about the system with different control laws, going from a simple to a more complex control law. A relation between a hypothesis and a conclusion on form that was used just before occurred four times. Two of these involved the transition from a conclusion about the system without a control law to a hypothesis about the system with a control law. The other two transitions involved systems with a simple and a more complex control law. We like to illustrate this with the following example:

> CONCLUSION: A proportional control law cannot prevent oscillation. However, in the long run it will bring the ship on course.
> HYPOTHESIS (next form): A proportional and integral control law will do the job. Disruptions of the system occur mainly in the lower frequency range.

The link between the conclusion and the following hypothesis is primarily the observation that you need more than a proportional control law. The subjects just added one element to the control law.

Posttest. At the end of the lab session, all subjects were given a posttest that consisted of seven multiple-choice questions. These questions tested qualitative insight in the domain. The test was not extensive because of the limited time available.

The mean of the score of all subjects was 4.8 (*SD* = 1.3). Three of the four experimental groups scored 4.7 or 4.8. The group Domain specific—Hypotheses scored 4.3 (*SD* = 1.6). The control group had a score of 5.2 (*SD* = 1.1). The only significant difference was between these last two groups ($t = 2.33$, $p < .05$).

Summary and Conclusions

In the present studies we tried to gain insight into exploratory learning processes. We also evaluated the impact of instructional support measures on these processes.

In charting the exploratory study process we identified a total number of 22 detailed learning processes. We found that students made little use of some of the exploratory learning processes and that this was most likely caused by problems they had with the valid applications of these exploratory processes.

In Study 2 we analyzed the statements that students made on fill-in forms as they worked with a simulation. Analysis was done in a stepwise order. At each level students gained scores that expressed a percentage of correctness relative to some maximum score. The overall (overall experimental conditions and all subjects) average scores for each level are depicted in Table 6. Table 6 clearly shows that the bottle neck in exploratory learning is the valid performance of exploratory learning processes. Students were quite active, and once they made a statement that was valid in terms of a specific learning process they did not seem to have trouble with the domain itself or with relating different statements to each other. These results are not caused by the sequence of levels. We have analyzed the statements that were not valid at the learning process validity level and assessed if they were domain correct. Overall this was the case (almost 90% of these statements were correct).

More specifically we have seen that the transformative process generation of hypotheses was a different task. Shute and Glaser's (1990) findings substantiate the fact that this is a crucial process. They found that hypothesis generation was one of the most predictive indicators of successful learning with "Smithtown" their Intelligent Tutoring System on Economics. Comparing hypothesis-driven inquiry skills and data-driven inquiry skills (theorists and experimenters, respectively, in terms of Klahr and Dunbar [1988]), Shute and Glaser (1990) found that the former approach is the most effective. Moreover, successful subjects concurrently use both.

A related problem for our students was the difference between a hypothesis and a prediction. These two processes were frequently mixed up. Further, subjects had considerable trouble

Table 6
*Mean Scores (*M*) and Standard Deviation (*SD*) of the Total Scores (Over All Conditions, Subjects, and Cells) on Each Level of Analysis*

Analysis level	Total score *M*	Total score *SD*
Activity level (cells)	84.7	14.4
Learning process validity	41.9	7.5
Domain correctness	80.4	12.7
Consistency	90.1	24.1

Note. At the fifth level of analysis, the overall strategy level, we especially wanted to analyze the development of successive hypotheses and the relation between a hypothesis and the conclusion on a previous fill-in form. At the learning process validity level we already concluded that subjects stated little hypotheses, thus leaving insufficient data for analysis at the fifth, overall strategy, level.

with an adequate performance on data interpretation and drawing conclusions. Both of our studies showed that data interpretation was mostly done at a rather shallow level. In Study 1 subjects usually made local interpretations; in Study 2 they scored low on this learning process. For the process of evaluating, both studies showed that generalizations were hardly made. Again, Shute and Glaser's (1990) study substantiate that this is an important process and that this process serves as a good predictor for successful performance.

A second major aspect of our studies was the impact of the different instructional support measures that we designed. Although a direct comparison to the results of Study 1 is impossible, we feel that the subjects in Study 2 showed a higher activity on the characteristic exploratory learning processes. This impression is supported by the global activity level (see Tables 2 and 3). Furthermore, within Study 2, there was a consistent trend in the data that the experimental group with the highest level of instructional support scored high on all analysis levels that we used.

In Study 2 we found a number of effects of the instructional measurements in this study. At some of the levels of analysis (global activity, learning process validity for the cell CONCLUSION, and domain correctness) the groups with hypotheses already provided showed significant better results.

Although the results were not conclusive, support of exploratory learning processes is promising and under study. Not only on-line support, but also directly training exploratory skills might improve the results of exploratory learning. Shute and Glaser (1990), for example, recommend tutoring on the scientific inquiry skills. Also, Friedler, Nachmias, and Linn (1990) show successful instruction with prediction and observation forms. Furthermore, recent studies also recommend to relate learner attributes to instructional support (Shute, 1990, 1991) and domain characteristics, (Glaser, Schauble, Raghavan, & Zeitz, 1990).

An important question is of course: What is the effect on performance test? Owing to practical reasons the test that we could give in Study 2 was a very limited one. Results, however, did certainly not show an advantage of the experimental groups over the control group. Moreover, the Domain specific—Hypotheses group (i.e., the group with the highest level of support on both conditions) had a significant lower score than the control group. Results of recent studies (de Jong, de Hoog, and de Vries, 1991) showed similar results. A possible explanation is that the subjects in this group were more involved in the additional aspects of exploratory learning. As we look at our data this is plausible. The Domain specific—Hypotheses group had high scores on the four levels of analysis in which we had sufficient data.

The studies reported here involved a specific domain and were conducted within a regular curriculum.

The domain involved (control theory) can be seen as representative for domains that are used for learning and instruction with computer simulation. It is a rather complex domain with a number of central key concepts that have dynamic relations. We therefore expect the same phenomena as we have found here to be valid for other domains.

Performing experiments in regular curricula means that both experimental rigor and possibilities for implementing experimental conditions are endangered. The great advantage is that research is done in a situation for which the conclusions are highly relevant, so facilitating ecological validity. Furthermore, the impact of the experimental instructional measures is necessarily small compared to the regular instruction. This means that students in the experimental group hardly had time to get adjusted to a brand new way of learning and instruction. Despite some of the hopeful results, it is likely that students need to work in this way for a longer period of time, before more significant results will appear.

Appendix A

Exploratory Learning Processes

Category		Definition
TRANSFORMATIVE PROCESSES		
Analysis		
1	**Looking for and/or finding of information**	The learner tries to find domain information by searching in text books, additional material, asking a tutor etc.
	Model exploration	Identifying and relating variables and parameters in the model and indicating general properties of the model.
2	Identifying	Identifying the variables, parameters of the model.
3	Qualitative relation	Making the relations within the model explicit by qualitative statements.
4	Quantitative relation	Making the relations within the model explicit by quantitative statements.
Hypothesis generation		

Appendix A *(Continued)*

Category		Definition
5	**Hypothesis generation**	The formulation of a relation between one or more variables (input and output) and parameters in the simulation model. A hypothesis is stated with the intention of testing it.
Testing		
6	**Designing an experiment**	Indicating what will be changed in a simulation model.
	Making predictions	A prediction states the expectation of a simulation run outcome as the result of designated value attributions to variables.
7	Qualitative prediction	The expectation is stated in qualitative terms.
8	Quantitative prediction	The expectation is stated in quantitative terms.
	Learner activities	Changing variable values, etc.

Appendix A *(Continued)*

Category		Definition
9	Manipulation of variables / internal parameters	To handle, control or change the (values of the) variables or internal parameters which describe system properties.
10	Manipulation of external parameters	To handle, control or change the (values of the) external parameters which represent the relation with the environment.
	Data interpretation	Interpreting the data without a direct reference to model relations. The learner can do this in a local manner or at a conceptual level.
11	Local output interpretation	To give one's understanding of the meaning of the output as such (noticing specific characteristics of the output, for example: this is an asymptotic relation).
12	Conceptual output interpretation	To give one's understanding of the meaning of the output on a conceptual level (e.g., comparing with other known graphs or data or to information from other sources).

Appendix A *(Continued)*

Category		Definition
13	Supportive processes for interpretation	Performing supportive action for interpretation of the output e.g., changing the range on an axis.
Evaluation		
14	**Evaluating / Judging**	Here the actions of the learner and the results thereof are evaluated (e.g., "I shouldn't have done this experiment.").
15	**Generalizing**	In generalizing the learner puts his actions and the results thereof in a broader context both as learning processes or as domain information (e.g., "This is an approach I think I can use more often.").
REGULATIVE PROCESSES		
16	**Planning**	Planning can be at the level of the complete study process, or at the level of one of the phases indicated above. It indicates devising an outline/scheme for what to do.

Appendix A *(Continued)*

Category		Definition
17	**Verifying**	Verifying is checking correctness of actions and results at a conceptual level (e.g., "Did I use the right parameter .... , let's see.").
18	**Monitoring**	In monitoring the learner observes and keeps track of his/her own study process (e.g., "So, let's see if we have what we want ...").
PCMATLAB OPERATIONS		
19	**Operations of PCMatlab**	Processes for the operation of PCMatlab (user-interface).
GENERAL PROCESSES		
20	**Calculating**	Calculating
21	**Making notes**	Making notes
22	**Off-task**	Off task remarks

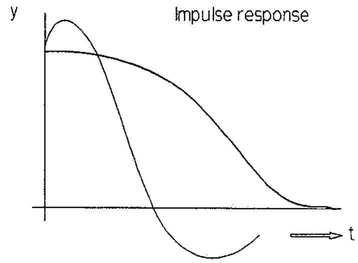


Figure 2. Example of students' notes in the cell PREDICTION.

Appendix B

Example of Data Analysis at Level 2: Learning Process Validity

We will illustrate the scoring of learning process validity by discussing the scoring of one pair of students. This pair was a member of the group that received domain specific information and had free fill-in forms. The form shown was the third form that they had filled in.

In the cell HYPOTHESIS these students noted down: If $K = b^2/4a$, then the system is most stable. This means that they state an optimal choice for the feedback amplification (K) with regard to the stability of the system. On the previous form students had already made the choice for a specific type of control law (a proportional control law) and now they make a choice for the value of the parameter in this law.

This statement received the full score for stating a hypothesis. Both dependent (stability) and independent variables (K) and a relation (optimal level) between them was indicated.

In the cell EXPERIMENT the students only noted down "Impulse response". This means that they indicated the output that they wanted to look at. They did not specify the following two aspects: which variables (in the concrete situation) to vary and the values to give to the variables to be manipulated. As a consequence, they received only 1 out of 3 possible credit points for the cell EXPERIMENT.

In the cell PREDICTION the students correctly stated a prediction, indicating the expected results of an experiment. They did this in a graphical way (see Figure 2).

For the cell DATA INTERPRETATION we used six criteria in our assessment. As is shown in Figure 3 the students indicated on their form only one of these criteria. They noted down the

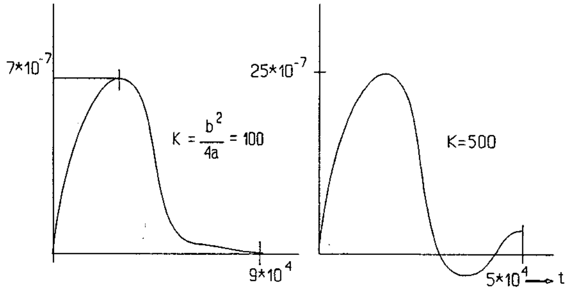


Figure 3. Example of students' notes in the cell DATA INTERPRETATION.

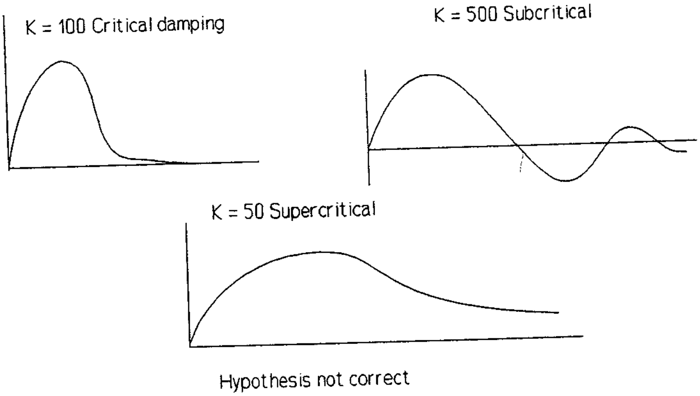


Figure 4. Example of students' notes in the cell CONCLUSION.

(graphical) output of the simulation run. Next to the value for K they chose, they also took another value for K (K = 500) to show that with this K it takes more time to return to the initial position. They did not (a) discuss the characteristics of the output; (b) make a comparison to the prediction; (c) infer important characteristics of the system; (d) relate output to the experiment; or (e) make a comparison to other experiments, graphs, or data. The conclusion section is given in Figure 4. What we see is that the students gave some data interpretation. They indicated important characteristics of the system by stating for which K there is critical damping, subcritical damping, and supercritical damping. Here they concluded that the hypothesis that was stated is incorrect. This is, by the way, a correct conclusion because there is a whole range of Ks for which stability is maximal.

References

Berkum, J.J.A. van, & Jong, T. de (1991). Instructional environments for simulations. *Education & Computing, 6,* 305–358.

Böcker, H.D. Herczeg, J., & Herczeg, M. (1989). ELAB - An electronics laboratory. In D. Bierman, J. Breuker, & J. Sandberg (Eds.), *Proceedings of the 4th international conference on AI & Education* (pp. 15–25). Amsterdam: IOS.

Camacho, M., & Good, R. (1989). Problem solving and chemical equilibrium: Successful versus unsuccessful performance. *Journal of Research in Science Teaching, 26,* 251–272.

Ferguson-Hessler, M.G.M., & Jong, T. de (1990). Studying physics text; differences in study processes between good and poor performers. *Cognition and Instruction, 7,* 41–54.

Finegold, M., & Gorsky, P. (1989). Learning about forces: Simulating the outcomes of pupil's misconceptions. *Instructional Science, 17,* 251–261.

Friedler, Y., Nachmias, R., & Linn, M.C. (1990). Learning scientific reasoning skills in microcomputer-based laboratories. *Journal of Research in Science Teaching, 27,* 173–191.

Glaser, R., Schauble, L., Raghavan, K., & Zeitz, C. (1990, September). *Scientific reasoning across different domains (draft version).* Paper presented at the NATO ARW "Computer-based Learning and Problem Solving," Leuven, Belgium.

Hoog, R. de, Jong, T. de, Vries, F. de (1991). Interfaces for instructional use of simulations. *Education & Computing, 6,* 359–385.

Jong, T. de, Hoog, R. de, & Vries, F. de (1991). *Coping with complex environments: The* *effects of navigation support and a transparent interface on learning with a computer simulation of decision support theory.* Manuscript submitted for publication.

Jong, T. de, & Ferguson-Hessler, M.G.M. (1991). Knowledge of problem situations in physics: A comparison of good and poor performers. *Learning and Instruction, 1,* 289–302.

Jong, T. de, & Njoo, M. (1992). Learning and instruction with computer simulations: Learning processes involved. In E. de Corte, M. Linn, H. Mandl, & L. Verschaffel (Eds.), *Computer-based learning environments and problem solving* (NATO ASI series F: Computer and Systems Series) (pp. 411–427). Berlin: Springer.

Joolingen, W.R. van, & Jong, T. de (1991a). Characteristics of simulations for instructional settings. *Education & Computing, 6,* 241–262.

Joolingen, W.R. van, & Jong, T. de (1991b). *Supporting hypothesis generation by learners exploring an interactive computer simulation.* Manuscript submitted for publication.

Klahr, D., & Dunbar, K. (1988). Dual space search during scientific reasoning. *Cognitive Science, 12,* 1–48.

Lavoie, D.R., & Good, R. (1988). The nature and use of prediction skills in a biological computer simulation. *Journal of Research in Science Teaching, 25,* 335–360.

Lodewijks, H.G.L.C. (1985). Wat is onderzoek van onderwijsleerprocessen? [What is research of learning processes?]. *Jaarverslag jaarboek 1984.* 's Gravenhage: SVO.

Njoo, M., & Jong, T. de (1991). Learning processes of students working with a computer simulation in mechanical engineering. In M. Carretero, M. Pope, R.J. Simons, & J.I. Poze (Eds.), *Learning and instruction: European research in an international context* (pp. 483–495). Oxford: Pergamon.

Rivers, R.H., & Vockell, E. (1987). Computer simulations to stimulate scientific problem solving. *Journal of Research in Science Teaching, 24,* 403–415.

Reimann, P. (1989). Modeling scientific discovery learning processes with adaptive production systems. In D. Bierman, J. Breuker, & J. Sandberg (Eds.), *Artificial intelligence and education; synthesis and reflection. Proceedings of the 4th International Conference on AI and Education* (pp. 218–227). Amsterdam: IOS.

Shute, V.J. (1990, April). *A comparison of inductive and deductive learning environments: Which is better for whom and why?* Paper presented at the 1990 AERA Annual Meeting, Boston, MA.

Shute, V.J. (1991, April). *A comparison of learning environments: All that glitters. . . .* Paper presented at the 1991 AERA Annual Meeting, Chicago, IL.

Shute, V.J., & Glaser, R. (1990). A large-scale evaluation of an intelligent discovery world: Smithtown. *Interactive Learning Environments, 1,* 51–77.

Swanson, J.H. (1990, April). *The effectiveness of tutorial strategies: An experimental evaluation.* Paper presented at the 1990 AERA Meeting, Boston, MA.

Towne, D.M., Munro, A., Pizzini, Q.A., Surmon, D.S., Coller, L.D., & Wogulis, J.L. (1990). Model-building tools for simulation-based training. *Interactive Learning Environments, 1,* 33–50.

Veenman, M.V.J., & Elshout, J.J. (1990). De meerwaarde van een goede probleemaanpak. [The surplus value of a proper problem approach]. *Tijdschrift voor Onderwijsresearch, 15,* 337–347.

White, B.Y., & Frederiksen, J.R. (1990). Causal model progressions as a foundation for intelligent learning environments. *Artificial Intelligence, 42,* 99–157.

Manuscript accepted March 30, 1992.