Exploratory learning with a computer simulation : learning processes and instructional support

Citation for published version (APA):
Njoo, M. K. H. (1994). *Exploratory learning with a computer simulation : learning processes and instructional support*. [Phd Thesis 1 (Research TU/e / Graduation TU/e), Industrial Engineering and Innovation Sciences]. Technische Universiteit Eindhoven. https://doi.org/10.6100/IR412686

DOI:
10.6100/IR412686

Document status and date:
Published: 01/01/1994

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.

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Exploratory learning with a computer simulation:

learning processes and instructional support

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Exploratory learning with a computer simulation: learning processes and instructional support

CIP-DATA KONINKLIJKE BIBLIOTHEEK, DEN HAAG

Njoo, Melanie Kiok Hua

Exploratory learning with a computer simulation : learning
processes and instructional support / Melanie Kiok Hua
Njoo. - Eindhoven : Technische Universiteit Eindhoven
Thesis Eindhoven. - With ref. - With summary in Dutch.
ISBN 90-386-0233-2
Subjects headings: learning processes / computer simulation.

Exploratory learning with a computer simulation: learning processes and instructional support

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Eindhoven,
op gezag van de Rector Magnificus, prof.dr. J.H. van Lint,
voor een commissie aangewezen door het College van Dekanen
in het openbaar te verdedigen
op donderdag 10 maart 1994 om 16.00 uur

door

MELANIE KIOK HUA NJOO

geboren te Bandung

Dit proefschrift is goedgekeurd door de promotoren:

prof.dr. J.M. Pieters
prof.dr. D.G. Bouwhuis

Copromotor:

dr. A.J.M. de Jong

Het eerste deel van het onderzoek leidende tot dit proefschrift is uitgevoerd mede onder leiding van wijlen prof.dr. D.W. Vaags.

Aan mijn ouders

Aan Cooper

Financial support by BSO/Instruction Technology BV (Baarn, the Netherlands) for the publication of this thesis is gratefully acknowledged.

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INTRODUCTION

The main subject of this thesis is exploratory learning with computer simulations. During exploratory learning a learner actively acquires knowledge by means of inquiring or experimenting in an open learning environment. Several learning environments can facilitate exploratory learning but in this thesis the focus is on computer simulations. A computer simulation is a computer program that contains a model of a process, principle or device. A learner can manipulate variables or parameters in the model and the computer simulation shows the results of these manipulations.

For obtaining insight into exploratory learning with computer simulations, research of exploratory learning processes is needed. Moreover, results of the studies on exploratory learning processes can provide a framework for designing instructional support for computer simulations. In this thesis research of the following two aspects is presented:

- exploratory learning processes;
- instructional support for exploratory learning.

Chapter 1 will start with an overview of the theoretical concepts of this thesis. The main part of this thesis consists of empirical studies that have all been carried out in an educational context with the technical domain of control theory. A brief description of the domain and the educational context will be given in Chapter 2. Two studies will be reported in Chapter 3, which have led to an inventory of exploratory learning processes. Furthermore, two experimental studies will be reported in the Chapters 4 and 5, which evaluate the impact of instructional support for exploratory learning. Finally, conclusions from the theoretical and empirical work in this thesis will be given in Chapter 6.

CHAPTER 1

LEARNING AND INSTRUCTION WITH COMPUTER SIMULATIONS

The main subject of this thesis is exploratory learning with computer simulations. For obtaining insight into this subject, research of exploratory learning processes is needed. Moreover, results of the studies on exploratory learning processes can provide a framework for designing instructional support for computer simulations.

In this first chapter the theoretical background of this thesis is given. First, learning is discussed from the cognitive viewpoint because the importance of learning processes is emphasized in this viewpoint. Secondly, exploratory learning is introduced. Three research areas that have served as a source of inspiration for the definition of exploratory learning are briefly presented. Thirdly, computer simulations are characterized as learning environments for exploratory learning. Furthermore, problems that learners encounter when they are learning with computer simulations are reported. In order to overcome some of these problems and to help learners to explore, it might be helpful to provide instruction for exploratory learning. To define types of instruction for exploratory learning several points of orientation have been used and these are discussed in the present chapter. Finally, the focus of the studies in this thesis is clarified and the research questions are addressed.

1.1 Learning from the cognitive viewpoint

Contemporary learning theories describe learners as active agents of knowledge acquisition. Learners are no longer seen as passive respondents to various environmental stimuli as was the case in the behaviourial tradition. On the contrary, cognitive approaches to learning stress that learning is dependent upon mental activities of learners. Meaning and comprehension must be constructed by individual learners (Shuell, 1986; Wildman, 1981; Wittrock, 1974).

Learning theory and research on learning have been strongly influenced by cognitive psychology and, more recently, by constructivism. In the present section the influence of both cognitive psychology and constructivism is discussed. The discussion of cognitive psychology shows the emphasis on learning processes rather than on behavioural responses. Two models of learning are presented to gain insight into exploratory learning. In addition, constructivism shows even stronger emphasis on individual learning processes.

Before the influence of cognitive psychology is discussed the concept of *learning process* is addressed for two reasons. First of all, learning processes will receive great emphasis in this thesis. Second, the concept can be a source of terminological confusion. As Kirby (1984) indicated, the basic problem is that 'process' can refer to the general category of cognitive functions or to a subset of cognitive functions. In this thesis, the concept of 'learning process' does not refer to the general category of cognitive functions. For this overall process of knowledge acquisition the term *'learning'* will be used. The concept of 'learning process' is defined as a significant combination of cognitive functions that can be characterized as a class of mental operations e.g., evaluating or generalizing. However, the concept does not address the description of cognitive functions such as in the information-processing approach. In the information-processing approach learning is analyzed into a sequence of ordered stages. Each stage reflects an important step in the processing of information (Anderson, 1990; Gagné, 1974). Commonly identified processes in this approach are storage, encoding, matching, and retrieval of information. In this thesis 'learning process' does not refer to these detailed cognitive functions but to a combination of these functions. During learning, information that is available to a learner from an external source (e.g., tutor, book, or computer-based learning environment) is transformed into a learner's knowledge base. In general, learning processes result in learning and control of learning.

For a better understanding of the concept of 'learning process' a distinction from two other concepts should be made. First, *learning goals* should not be confused with learning processes. Learning goals, which is a concept that received extensive attention in education, are considered to be the desired outcomes of learning. The studies in this thesis will not only address learning outcomes but will mainly be concerned with the processes preceding the attainment of the desired learning goals. Another distinction should be made between learning processes and *instructional actions*. Learning processes are mental operations of a learner whereas instructional actions are operations of an external source such as a tutor. In this thesis both learning processes and instructional actions will be studied, taking into account the relations between them.

A final remark on learning processes concerns the method of research. Learning processes are cognitive processes and not directly observable. Therefore, specific methods have to be used to determine cognitive processing. A familiar example of such a method is thinking-aloud-protocols (Ericsson & Simon, 1984).

1.1.1 Cognitive psychology

One of the important consequences of the influence of cognitive psychology on learning has been that performance and cognitive abilities have been analyzed in terms of learning processes involved (Shuell, 1986). Attention was given to higher level processes in learning. Additionally, the role of metacognitive processes, such as planning and monitoring, was acknowledged. Behaviour was no longer seen as the ultimate goal but rather as a possible result of learning. Emphasis was given to processes of knowledge acquisition and to knowledge representations in a learner's knowledge base.

Two influential models in this tradition are *schema theory* and *ACT* theory*. Each model presents a representation of learning and general learning processes which can form a basis for an inventory of exploratory learning processes.

The first model, schema theory (Rumelhart, 1980; Rumelhart & Norman, 1978), describes internal representations of knowledge. These internal representations of knowledge are referred to as *cognitive structures* or *schemata*. A schema consists of a set of interrelated concepts. The concepts can be other schemata themselves or part of other schemata. Thus, schemata are organized as interrelated knowledge structures. The representation of knowledge in schemata also facilitates the development of a network of interrelations. Therefore, schemata are actively engaged in the comprehension of information.

Learning processes in this model are involved with modifications of schemata. Internal representations are formed through two processes (Wildman, 1981). The first process is assimilation of new information into existing memory networks or structures and the second process is accommodation of cognitive structures to new information.

Three more specific processes are mentioned in schema theory: accretion, tuning, and restructuring (Rumelhart & Norman, 1978).

- *Accretion*
  In accretion, new knowledge elements are added to existing schemata. In this way comprehension is reached. Accretion can be regarded as fact learning because there are no structural changes in the information-processing system itself.

- *Tuning*
  During tuning, modification of existing schemata takes place as a result of the application of knowledge. Tuning can bring the schemata into better congruence with the functional demands placed on them and can improve accuracy, generality, and specificity.

- *Restructuring*
  Within restructuring, creation of new schemata and development of new concepts occurs. Restructuring takes place when new information does not fit currently available schemata or when the organization of existing data structures is not satisfactory. The new structures, which are a result of restructuring, allow for new interpretations of knowledge, for different (improved) accessibility to that knowledge, and for changes in the interpretation. The outcome is the acquisition of new knowledge.

The second model is *ACT* theory* (Anderson, 1983; Anderson, Kline, & Beasley, 1980). ACT stands for Adaptive Control of Thought, and '*' stands for a revised version of this theory. ACT* is a theory of the architecture of cognition and the basic cognitive processes which can be applied to this architecture. Its preconception is that there is one common cognitive system for higher level processing. The basis for this underlying cognitive system is formed by *productions*. A production is a condition-action pair. This production rule specifies the action that should be executed when the condition is valid. With production rules, ACT* focuses on skill acquisition. With skills is meant *procedural knowledge* i.e., knowledge about how to do things. Skills do not only refer to motor skills but to cognitive skills as well. The learning strategy of ACT* for procedural knowledge is 'learning by doing'. This means that a learner actually has to execute a skill in order to learn it.

ACT* distinguishes three stages in skill acquisition: a declarative stage, a knowledge compilation stage, and a tuning stage. In the declarative stage, a learner makes use of declarative representations and performs interpretive applications of these representations. In the second stage the skill is further compiled into a task-specific procedure that can apply the knowledge directly. Knowledge compilation makes use of the processes *composition* and *proceduralization*. During composition, a sequence of productions that follow each other in solving a particular problem are combined into a single production that has the same effect. Proceduralization creates versions of the productions that no longer require domain specific declarative information. Learning still goes on after a skill has been compiled into a task-specific procedure. In the final stage, the tuning stage, productions are modified or refined and methods of selectivity are added. Processes such as generalization, discrimination, and strengthening are involved[1].

- *Generalization*
  Generalization extends the range of applicability of the production rules.

- *Discrimination*
  As contrasted with generalization, discrimination restricts the range of applicability to adjust to appropriate circumstances.

- *Strengthening*
  With strengthening, better production rules are strengthened and poorer production rules are weakened. It can be considered as an evaluation of the changes caused by generalization or discrimination.

Schema and ACT* theory have their own emphasis. Schema theory is concerned with knowledge representation whereas ACT* is concerned with (cognitive) skill acquisition. Furthermore, schema theory is based on knowledge structures whereas ACT* is based on rules. However, Anderson (1983) criticized that schema theory does not provide a framework for a learning theory because schema theory does not make a distinction between procedural and *declarative knowledge* (i.e., factual knowledge). I do not share this criticism. For understanding learning, a model of knowledge representation is as functional as a model of knowledge acquisition because learning is not only

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[1] Anderson (1989) has presented a successor of ACT* named Penultimate Production System (PUPS). PUPS primarily differs from ACT* on its principles of induction. The process of generalization is replaced by an analogy-based type that adds constraints to the generalizations. Furthermore, mechanisms of discrimination and causal inference are added.

concerned with acquisition of new knowledge but also with modification of existing knowledge.

1.1.2 **Constructivism**

Cognitive psychology has influenced learning theory for over three decades. More recently the current trend is acknowledged as *constructivism* with even more emphasis on individual learning processes and knowledge representations. Jonassen (1991) argued that in constructivism, experiences of individual learners are placed in a central position. These experiences form personal constructions that are shaped by what is already known by an individual learner. Several authors (Bruner, 1972; Duffy & Jonassen, 1991; Jonassen, 1991; Tobin, 1992) described the paradigm shift from *objectivism* to constructivism in the field of learning psychology. Jonassen (1991) uses the term 'objectivism' to refer to a set of assumptions such as existence of reliable and stable knowledge of the world, transition of knowledge to learners, and learning as assimilation of the objective reality. The philosophical assumptions underlying constructivism regard learning as processes of actively interpreting and constructing individual knowledge representations whereas objectivism conceptualizes it as processes for representing and mirroring reality (Jonassen, 1991). Duffy and Jonassen (1991) even argued that much of cognitive psychology is based on the objectivistic viewpoint. Their argument is that cognitive psychology explicitly acknowledges the independent existence of information with the information-processing approach. Therefore, learning is simplified to acquisition of independent information representations.

Two different views coexist within constructivism. The radical variant argues that reality only consists in the learner's mind and accordingly denies the existence of reality. In the moderate viewpoint processes of negotiation and consensus building are acknowledged. These processes result in shared constructions and these shared constructions are acquired by individual learning processes.

With constructivism, the importance of learning processes is even more emphasized than in the information-processing approach. Without individual learning processes there would be no individual knowledge base. Even though the significance of learning processes is acknowledged, constructivism has not (yet) succeeded in a significant contribution to the identification of learning processes. Jonassen (1992) referred to the more general processes such as relating information to prior knowledge, interpreting new information in the light of prior knowledge, and reorganizing prior knowledge on the basis of newly acquired knowledge. These processes, however, were already known from the information-processing approach.

Another point of concern is that constructivists seem to deal with the practical applications of constructivism. Although, Jonassen (1992, p. 2) argued that:

> ... people do not learn from computers, books, videos, or other devices that were developed to transmit information. Rather, learning is mediated by thinking (mental processes).

literature on constructivism has strongly focused on instructional tools such as computer programs. For example, Spiro, Feltovich, Jacobson, and Coulson (1992) designed a hypertext system based on their constructivistic ideas. A hypertext system is a computer-based database with flexible and associative connections between units of information, resulting in an information network. Learners can revisit the information by crisscrossing. Scardamalia, Bereiter, McLean, Swallow, and Woodruff (1989) designed Computer Supported Intentional Learning Environments (CSILE). CSILE are educational knowledge media systems which allow learners to use several media to enter information into a common database. Learners can then link, retrieve, comment or rate the information. These instructional tools might be quite attractive and motivating for learners. However, their effects on learning processes and learning outcome need further study.

1.2 Towards a definition of exploratory learning

During exploratory learning learners actively acquire knowledge by means such as inquiring or experimenting in an open learning situation. Learners can explore a given domain in a more or less self-directed way. The two models in Section 1.1 provide a general framework for understanding learning but do not provide sufficient insight in exploratory learning. Until recently, there even was little specific research on exploratory learning and the processes that facilitate exploratory learning. Therefore, three specific areas of research were explored for acquiring insight in exploratory learning. These areas are:

- *problem solving*;
- *discovery learning*;
- *inductive learning*.

In the present section the three research areas and their significance for exploratory learning are discussed. Characteristics of the areas are combined into a definition of exploratory learning. Furthermore, some recent studies on exploratory learning are briefly discussed in the present section.

1.2.1 Problem solving

In the area of problem solving, Newell and Simon (1972) introduced the concept of *problem space*. A problem space is an internal representation of the environment in which problem solving takes place. A problem space consists of a number of components such as a set of *elements*. Each element represents a *knowledge state* in the problem solving task. A knowledge state is a set of information items that the problem solver knows or assumes on a certain point in the search process e.g., an initial knowledge state and a set of desired solution states. Problem solving is conceptualized as a search through the problem space of knowledge states until a desired solution state is found. A set of *operators*, named information processes, constitutes the search processes. Newell and Simon (1972) did not elaborate on these information processes and only mentioned those that operate upon elements. These processes are described at a very rudimentary level. The basic processes are discrimination, test, and comparison, and a number of processes that are concerned with creation such as reading and writing, designing, and storing elements. Other authors (Duffield, 1991; Gick, 1986) have also described problem solving as a search through a problem space. For a description of the problem solving processes they make use of information-processing models in which the problem representation and the solution process are distinguished. The solution process consists of a search through problem space for an appropriate solution.

With regard to problem solving a vast body of research exists. Two examples are Cronbach (1977) and Mettes and Gerritsma (1986). Cronbach (1977) described problem solving as a complex combination of cognitive actions such as interpretation, trial, and confirmation. He divided problem solving into two main processes: divergent and convergent thinking. Divergent thinking consists of recalling, recognizing, and inventing alternative solutions. Convergent thinking consist of reducing the array of possibilities and choosing an adequate solution. Mettes and Gerritsma (1986) described three general stages of problem solving. The three stages are preparation, execution, and control. During the first stage the processes of orientation and planning take place. In the execution stage a transformation and determination of the solution is given and followed by an evaluation. During the final stage of control the results are interpreted. The two examples are analogous to the model of Newell and Simon (1972). In both Cronbach (1977) and Mettes and Gerritsma (1986) two significant characteristics of problem solving can be distinguished. First, problem solving is goal-oriented towards a solution of the problem. Second, the problem solving processes are concerned with movements between solution states.

1.2.2 Discovery learning

In the field of educational psychology there has been strong interest in discovery learning (e.g., Ausubel, Novak, & Hanesian, 1978; Bruner, 1966). Actually, 'discovery' is a very ambiguous term (Hawkins, 1966). It does not exclusively imply the discovery of new, previously unknown, entities or facts but rather refers to ways of classifying and relating known information. Therefore, it is useful to make a distinction between *autonomous* and *guided discovery learning*. Autonomous discovery resembles, what is assumed as, the classical scientific discovery method. Guided discovery refers to discovery in an instructional context. In this thesis the latter type of discovery is addressed. According to Ausubel et al. (1978) the processes of discovery include:

- hypothesis formulation;
- hypothesis testing;
- determining the strategy of application;
- identifying fruitful approaches;
- using systematic and economic methods of inquiry.

While the discovery method might work well in scientific discovery, Ausubel et al. (1978) disputed the effectiveness of the discovery method in an educational setting. One of their main arguments is that learners need an adequate background in substantive and methodological principles of the discovery method and learners often lack this background.

In general, however, discovery learning allows for and encourages active experimentation and exploration. Learners can discover important concepts and principles, or find solutions to problems for themselves. It encourages reflective thinking and self regulation. The essential feature of discovery learning is that the content of what is to be learned is not given, but must be discovered by a learner before it can be meaningfully incorporated into the learner's cognitive structure. The processes involved are for example: rearrange information, integrate it with existing cognitive structure, and reorganize or transform the integrated combination in such a way as to generate a desired end-product or discover a missing means-end relationship.

Kolesnik (1976) mentions some related discovery processes. According to him learning by discovery is essentially a matter of recognizing relationships. It occurs when we come to perceive a situation in a new way, extrapolate our information, draw inferences or when we restructure our experience in such a way that new patterns or relationships emerge.

1.2.3 Learning by induction

Learning by induction takes place when a learner draws inductive inferences from tutor- or environment-provided facts (Michalski, 1987). These processes involve generalizing, transforming, correcting, and refining knowledge representations. To perform inductive inferences, one needs some additional knowledge to constrain the possibilities and guide the inference process towards one or a few most plausible hypotheses. In his overview of fundamental learning strategies Michalski (1987) distinguished the following inductive learning strategies: learning from examples, by experimentation, observation, or discovery. These strategies include a variety of processes, such as creating classifications of given observations, discovering relationships and laws governing a given system, or forming a theory to explain a given phenomenon. Additionally, because inductive learning can involve many different concepts, a learner must be able to plan and manage the available time and resources to acquire several concepts at once.

Greeno and Simon (1984) recognized two approaches in inductive learning and identified them as the top-down and bottom-up method of inductive inquiry. The top-down method involves hypotheses generating, hypotheses evaluating, and modifying or replacing hypotheses that are found to be incorrect. The bottom-up method involves storing information about experimental outcomes and making judgements about new outcomes on the basis of similarity or analogy to the stored information.

Michalski (1987) and Greeno and Simon (1984) contributed significant input for the identification of exploratory learning processes. In general, however, drawbacks of most studies in the area of inductive learning are that this subject is studied in abstract domains and studies are usually restricted to concept identification or concept formation (Anderson, 1990; Holland, Holyoak, Nisbett, & Thagard, 1989). Identification and formation of concepts are quite restricted learning goals and cannot be compared to cognitive complex processes in real-world settings (Reimann, 1991; Schank, Collins, & Hunter, 1986). Shute and Glaser (1990) recommended a more active process of induction. They made a distinction between a passive and an active form of induction. Most literature and studies on inductive learning have focused on the passive form which consists of inducing a rule or classifying relatively abstract stimuli into categories on the basis of experimenter-controlled presentation of predetermined instances. In the active process of induction, learners can select variables, design instances, and interrogate their existing knowledge and memory for recent events. Active induction consists of applying interrogative skills and organizing information. With active induction, learners explore and generate new data and test hypotheses with the data they have accumulated in the course of experimentation. Shute and Glaser (1990) believe that active induction can contribute to a rich understanding of domain information.

1.2.4 Exploratory learning

In Sections 1.2.1 through 1.2.3 three research areas were discussed. Problem solving, discovery learning, and learning by induction constitute a general framework for a definition of exploratory learning. Characteristics of the areas show great similarities. Frequently, a concept in one research area is defined in terms or characteristics in one of the other research areas. For example, Glaser (1966) stated that discovery learning can be characterized by inductive sequences and Greeno and Simon (1984) considered induction as a specific type of problem solving. Simon and Lea (1974) even presented a unified view of problem solving and rule induction. In their view there are two similarities between problem solving and induction. First, in both approaches the fundamental search processes (generating, testing, and selecting) and inference processes are organized similarly. Second, the same general methods can be applied (e.g., means-ends analysis, matching, generate-and-test). Simon and Lea (1974) also addressed the differences between problem solving and induction.

Differences are found in the kind of problem spaces that are searched. Induction requires a search in two spaces:

- a space of instances, stimuli, or data;
- a space of possible rules (structures, patterns, or relations).

Simon and Lea (1974) described problem solving as a search through one space, usually the space of rules. The nature of one of the search processes, the test process, also distinguishes rule induction from problem solving. With induction, the test is not applied directly to the rules but is tested against the instances. Thus, learning by induction requires a movement between instances and rules whereas for problem solving it is sufficient to test the rules themselves. Recently, learning by induction is applied in more concrete and real-world settings. Here, learners do not have to induce understanding of an abstract concept but have to inquire a complex domain. Studies of *scientific inquiry*, *scientific reasoning*, or *scientific discovery* are numerous. In this thesis these concepts are referred to as exploratory learning and it is argued that exploratory learning consists of a combination of characteristics of the three presented research areas: problem solving, discovery learning, and learning by induction.

The similarities between the areas lie in the constructive character of the learning processes. In all three approaches, learners can formulate general principles or procedures and can discover this information by themselves. The general idea is that this active and constructive attitude of a learner encourages meaningful incorporation of information into the learner's cognitive structure. The area of problem solving shows an emphasis on goal-oriented processes. These goal-oriented processes toward a solution are most strongly recognized in the area of problem solving but also hold for the areas of discovery learning (e.g., discovery of a principle) and learning by induction (e.g., identification of a concept). More recently, Langley, Simon, Bradshaw, and Zytkow (1992) also argued that scientific discovery and problem solving are based on the same general mechanisms of the cognitive approach (see Section 1.1). In this thesis discovery learning and learning by induction are also considered and recent developments in constructivism are added to broaden the perspective of exploratory learning.

A recent experimental study that looked directly at exploratory learning is the one by Klahr and Dunbar (1988). They proposed a general model named Scientific Discovery as Dual Search (SDDS), which is comparable to Simon and Lea's (1974) model. The fundamental assumption is that scientific discovery requires search in two related problem spaces: a hypothesis and an experiment space. Hypothesis space is the space that represents all possible hypotheses. Experiment space represents all experiments that can be conducted. Another difference is made by Shute and Glaser (1990). They distinguished data-driven and hypothesis-driven experimenting. Data-driven experimenting focus on local experiments with a limited scope. Hypothesis-driven experimenting aims at generalizing results of local experiments for induction of general principles. In Shute and Glaser's (1990) study, hypothesis-driven experimenting was highly correlated with successful learning. Furthermore, other authors have studied exploratory learning (Friedler, Nachmias, & Linn, 1990; Lavoie & Good, 1988). These and other studies on exploratory learning processes are further discussed in Chapter 3 of this thesis.

1.3 Computer simulations

Exploratory learning requires an open learning environment that allows learners to actively acquire knowledge. *Computer simulations* present such an open learning environment. A computer simulation is a program that incorporates a model of a process, phenomenon, or system. The simulation program provides a description of the state of the model and shows state changes as a result of manipulations. The user is able to control input variables of the model and examine the resulting changes in output. A *simulator* is the device that performs the simulation. In the case of computer simulations the simulator is the computer program. However, it is also possible that the appearance of a simulator more or less resembles the actual device that has to be operated (this is usually the case for operational or procedural simulations) e.g., for a simulation of the operation of a nuclear power plant the simulator can resemble the actual control panel of the plant. In this thesis the focus is on computer simulations. Therefore, the term simulation will indicate a computer-based simulation and is used to refer to the program itself as well as to the processes that take place in the program.

Simulations are applied in a number of fields such as research, policy, and design. Their goals can be to generate new insight, test new designs, predict future events, or see the future consequences of certain decisions. Simulation programs are also frequently used for education and training purposes. The most familiar advantages are of a practical nature. Simulations, compared to learning in a lab or training-on-the-job, can be less expensive, less time-consuming, less dangerous, and less stressful.

Apart from these advantages computer simulations offer powerful means for learning and instruction. First of all, simulations allow learners to apply previously learned knowledge in a practical situation (Mandl, Gruber, Renkl, & Reiter, 1993; Pieters & Treep, 1989; Reigeluth & Schwartz, 1989). Moreover, a computer simulation is well suited for exploratory learning since it can 'hide' a model that has to be 'discovered' by the learner (de Jong, 1991). This offers advantages for the learning processes, which result in 'deeper' processing of domain knowledge, as well as development of more general strategies (Breuer, 1989). Finally, a learner can be presented with situations like disasters or situations that are not possible in real life e.g., alternative realities or processes that would be difficult to perceive because of an extreme short or long time interval.

De Jong (1991) characterized instructional use of computer simulations by four attributes that have to be present:

- a computational underlying model;
- instructional goals;
- evocation of specific (exploratory) learning processes;
- the possibility for learner activity.

It is assumed that, through mediation of these four attributes, learners are active both in performing learning processes and in manipulating the underlying model. The last three attributes distinguish *instructional simulations* from plain computer simulations. Simulations for non-educational purposes can be used in education but mostly in these cases the three attributes have not explicitly been considered during the design of the simulation.

Instructional simulations can be embedded in an environment that gives learners additional support for learning with the simulation. These environments will be referred to as *simulation learning environments* and can make use of techniques from Artificial Intelligence (AI) that represent knowledge of domain, student, instruction, and interface in separate modules and generate the interaction with the learner during run-time. When AI techniques are used these environments are referred to as intelligent simulation environments or intelligent tutoring systems with a simulation component. Some examples of (intelligent) simulation learning environments are given in Section 1.5.3.

Computer simulations can be described by a number of characteristics. Some of these characteristics have been the basis for taxonomies of simulations. Welham (1986) mentioned three criteria to categorize simulations: the content of the simulation, the level of trainee interface, and the complexity level. Alessi and Trollip's (1985) taxonomy is an example of a classification based on the first criterium, the content of the simulation. They discriminated physical, procedural, situational, and process simulations. However, Welham's (1986) criteria and the taxonomy of Alessi and Trollip (1985) do not provide a framework for instructional simulations.

A framework that does approach simulations from the instructional viewpoint was given by van Berkum and de Jong (1991). Their classification categorize simulation learning goals in terms of the knowledge that has to be acquired. They distinguished three dimensions:

- kind of knowledge;
- scope of knowledge;
- encoding format of knowledge.

For each dimension van Berkum and de Jong (1991) distinguished two opposite characteristics. First, the kind of knowledge can be conceptual or operational. Conceptual knowledge consists of knowledge of principles, concepts, and facts of the simulation domain at hand. Operational knowledge consists of procedures that can be applied in the simulation at hand. Secondly, the scope of knowledge is either domain-specific or generic. Finally, the encoding format of knowledge, which refers to the representation of information, can be compiled or declarative. Compiled means that information can be applied directly and needs no explicit interpretation. Information that needs to be interpreted before it can be applied is named the declarative format.

Apart from the learning goal of an instructional simulation the most significant characteristic of a computer simulation is that the domain is presented as a model. Other studies (van Joolingen & de Jong, 1991; White & Frederiksen, 1987) made a broad distinction between quantitative and qualitative models. Entities of quantitative models are represented in numbers related by mathematical equations. For qualitative models the entities are given in less restricted propositions.

1.4 Problems with simulation-based learning

In the previous section a number of advantages of computer simulations were mentioned that depict simulations as a promising means of instruction. However, in practical educational settings it appears that learners have problems with simulation-based learning. A number of studies focused on the differences between successful en unsuccessful learners with simulations and mention divers problems. Dörner (1980; 1983) emphasized that learning about complex dynamic systems is a difficult task in itself. Furthermore, two major issues became evident from these studies (e.g., Lavoie & Good, 1988; Shute & Glaser, 1990):

- learners can have trouble with processes in exploratory learning;
- learners' low level of prior knowledge is related to unsuccessful exploratory learning.

Shute and Glaser (1990, p. 52) reported problems of unsuccessful learners that are associated with exploratory learning:

> First, many learners can induce regularities or patterns but do not treat them as hypotheses to be tested. Second, even when subjects realize that they should test a hypothesis, they may use faulty methods or procedures that do not guarantee that the inferences drawn on the data are reasonable and/or relevant to the world or system being observed.

They found that less successful learners in their study, generally, showed no higher level planning in designing and executing experiments. Their explorations were impulsive and not systematic e.g., they changed multiple variables simultaneously and made generalizations based on inadequate data. Furthermore, unsuccessful learners were not able to go beyond a local description of the situation and failed to conceive lawful regularities and general principles which hold for a class of events rather than for a local description.

Other studies also reported problems that are connected with exploratory learning processes. Klahr and Dunbar (1988) described that learners failed to seek for disconfirmation, tolerated disconfirming evidence, and abandoned verified hypotheses. Reimann (1989; 1991) reported that learners did not design experiments systematically and had difficulties with the identification of promising variables. Goodyear and Tait (1989) discussed that problems might occur because of lack of higher level skills that promote exploratory learning.

Apart from problems that are related to exploratory learning processes itself, several studies acknowledged the importance of prior (domain) knowledge. Low prior knowledge of the learner can cause considerable problems (Glaser, Schauble, Raghavan, & Zeitz, 1992; Goodyear & Tait, 1989; Hartley, 1988; Schauble, Glaser, Raghavan, & Reiner, 1991). Lavoie and Good (1988) reported that learners with low prior knowledge are unsuccessful in their explorations when they have to state predictions about the outcome of experiments.

The problems mentioned in the present section should not withhold the application of simulations in education. First of all, the advantages mentioned in Section 1.3 are significant for education. Secondly, the studies in the present section also reported of successful learners. These successful learners e.g., manipulated fewer variables per simulation run and tended to strive after generalizing their findings (Shute & Glaser, 1990). The problems reported in these studies indicated that detailed study is required for the design of simulation learning environments. With extra support unsuccessful learners might have less problems or could be helped to overcome problems.

1.5 Instructional strategies for exploratory learning

The studies in the previous section showed that learners can have problems with simulation-based learning. To prevent these problems or to help learners overcome problems, attention should be given to the instructional strategy that is used in learning with computer simulation. In the present section, characteristics of exploratory learning as an instructional strategy are studied.

In this thesis *instructional strategy* will be used to indicate a specific instructional method or approach. Strategy will be used for a general method such as 'exploratory learning' or 'receptive learning' but also for a variant of a general method such as 'cognitive apprenticeship'. The concept of *instruction* will be used for the overall process and the specific actions that can be used will be referred to as *instructional measures* or *instructional actions*. Instruction can be based on one instructional strategy or a combination of strategies.

Several authors reported that learners should be provided with additional instruction when they are learning with computer simulations. Unfortunately, most authors did not specify the instructional strategy or specific instructional actions. For example, Kearsley (1985) explained that well-constructed simulations can guide or coach the learner to minimize inefficiency. Steinberg

(1984) reported that learners have to be provided with sufficient guidance or advice, dependent on the purpose of the simulation, which is meant to direct learners' exploration and result in attainment of the stated goals.

In the present section, exploratory learning is studied as an instructional strategy, with the aim of specifying the instructional actions. Three sources can be explored to study the instructional strategy and actions for learning with computer simulations. The sources are:

- instructional strategies from problem solving, discovery learning and learning by induction;
- instructional implications of constructivism;
- examples of simulation learning environments.

In this section these sources are discussed and result in types of instructional actions.

1.5.1 Instructional strategies in literature on problem solving, discovery learning and learning by induction

In the three research areas from Section 1.2 (problem solving, discovery learning, and learning by induction) a number of instructional strategies and actions are mentioned. In the present section only a selection of these strategies is presented to give an indication of the instructional actions involved.

Gick (1986) mentioned several ways in which problem solving can be improved by instruction. This instruction is based on the distinction between *schema-driven* and *search-based* problem solving strategies. Schema-driven strategies are invoked directly by a problem schema. They involve little search for solution procedures, and result in direct implementation of the appropriate solution procedure. Search-based strategies involve search processes for the appropriate solution procedure and also make use of information gathering strategies. Typically, experts use schema-driven strategies whereas novices use search-based strategies.

Gick (1986) argued that problem solving can be improved by encouraging learners to use a schema-driven strategy. To accomplish this a number of instructional actions can be used. She suggested a distinction between *direct* and *indirect* instructional actions for teaching problem solving strategies. Examples of indirect actions are: using problems with low goal specifity at the initial stages of learning (Sweller, Mawer, & Ward, 1983) or using hints in the form of a diagram (Gick, 1985). A disadvantage of indirect actions is that learners must induce knowledge and this probably results in implicit knowledge. In addition, as indirect actions require learners to abstract the necessary strategic information, these actions might not work for all learners. Direct instructional actions for teaching problem solving strategies might therefore be more effective. An example of a direct action is to provide students with training in heuristics and an additional managerial strategy to organize the use of different heuristics (Schoenfeld, 1979a, 1979b).

Duffield (1991) also gave advice on the instructional strategy for problem solving. She argued that one should emphasize understanding instead of direct instruction and this should be accomplished by free exploration. Duffield's (1991) strategy gave attention to two aspects. First, instructional actions that can be organized before any learner's interaction e.g., in the choice and sequence of information presented. One of her prescriptions was to make sure that number and size of chunks of information should be appropriate for learners' expected level of expertise. These instructional actions can be considered indirect actions since they do not intervene learners' explorations. Second, she recommended instructional actions that intervene and direct learners' explorations e.g., prompt learners when previously learned knowledge is useful or make learners aware of the underlying principles and warn the learners of surface similarities.

Studies of discovery learning were generally in favour of guided discovery. Guided discovery implies the use of instructional actions during discovery processes of learners. However, these studies do not always offer explicit suggestions for these instructional actions. Kolesnik (1976) gave a description of discovery learning which emphasized that discovery is accomplished with a minimum of outside help. He propagated guided discovery learning, because of the efficiency of the learning processes, but no explicit instructional actions are discussed. He only recommended tutors to provide learners with facilities, encouragement, challenges, and opportunities in a free atmosphere. Gagné (1965) also discussed the role of instruction in discovery learning. The effect of instruction is to cut down search time and eliminate wild hypotheses beforehand. He concluded that attention is needed for the preparation phase of instruction to stimulate discovery but does not mention concrete instructional actions. Guidelines for instructing discovery learning are found in Glaser (1966). He presented two viewpoints. First, discovery learning can involve the scientific method and research skills and these should be instructed step by step.

Second, instruction for discovery learning can involve teaching of general heuristics.

Few studies of learning by induction focused especially on instruction. Shute and Glaser (1990) presented a viewpoint of instruction for learning by induction. They believed that active induction can be more facilitating to knowledge and skill acquisition as opposed to passive induction (see Section 1.2.3). Instruction for active induction should focus on strategies related to testing of generalizations.

When the strategies and actions in the present section are considered, it appears that the area of problem solving provides the most elaborated perspective on instruction. First of all, Gick's (1986) instructional actions were based on learners' problem solving strategies. Moreover, both Duffield (1991) and Gick (1986) made a functional distinction between a direct and indirect style of instruction for problem solving.

Furthermore, in Section 1.2.4 an intertwining between the concepts of learning processes of these three research areas was noticed. A similar intertwining of relevant concepts is also present for the instructional strategies and actions e.g., Shulman and Keislar (1966) remarked that discovery learning can result from inductive instruction.

1.5.2 **Instructional implications from constructivism**

In Section 1.1.2 constructivism was discussed. In the present section a number of constructivistic theories are reported that hold a number of innovative instructional actions. The theories are:

- situated cognition;
- knowledge negotiation;
- cognitive flexibility theory.

In *situated cognition* (Brown, Collins, & Duguid, 1989) the general idea is that knowledge is connected to the situation in which it is acquired or used. Therefore, learning should deal with real-life settings and transfer between contexts is not automatic. An example of situated cognition is *anchored instruction* (Bransford, Sherwood, Haffelbring, Kinzer, & Williams, 1990) that tries to anchor knowledge to meaningful contexts. Bransford et al. (1990) suggested the following instructional actions:

- anchor knowledge and skills to a meaningful context;
- address other contexts;
- look at domain from different viewpoints to acquire flexible knowledge;
- decontextualize.

Another instructional approach that is based on situated cognition is *cognitive apprenticeship* (Brown, Collins, & Duguid, 1989; Lajoie & Lesgold, 1989). The ideas of cognitive apprenticeship are based on vocational training situations. A teacher should act like a coach and make use of instructional actions such as *scaffolding* and *fading*. With scaffolding the learner receives support of the teacher and with fading this support is gradually diminished.

The basic principle of *knowledge negotiation* (Moyse, 1992; Moyse & Elsom-Cook, 1992) is that there is not a single correct representation of a domain but that the interpretation of the domain must be jointly constructed between tutor and learner. This implies the need for multiple representations and mechanisms to support negotiation. Knowledge negotiation is the general process by which the domain interpretation is constructed or chosen and the set of techniques and design methods by which the desired adaptation to the student is achieved.

Dillenbourg (1992) specified knowledge negotiation as a definition of a particular style of interaction between a learner and an environment. The choice of a particular type of interaction is a complex decision process based on knowledge about the domain, the learner, and the pedagogical methods. For the latter the assumption is that learners test their own representations in the learning environment. Dillenbourg (1992) gave an example of such a system: a collaborative learning system with a computerized co-learner which is also a novice in the domain.

Cognitive flexibility theory (Spiro, Feltovich, Jacobson, & Coulson, 1992; Spiro & Jehng, 1990) implies that a learner should be able to address and use their prior knowledge in a flexible way. A central issue is that knowledge is represented along multiple dimensions. Therefore, Spiro et al. (1992) are in favour of multiple knowledge representations as an instructional measure. This should maximize transfer and advance learning.

The three constructivistic theories share a number of similar ideas, such as:

- learning should take place in real-world situations;
- there is not a single correct or true representation of knowledge;
- learners should be presented with multiple knowledge representations.

Furthermore, these theories emphasize the individuality of each learner. In constructivism learners are encouraged to go beyond the information that is presented and make their individual representations.

1.5.3 **Examples of simulation learning environments**

A number of (intelligent) simulation learning environments appeared that comprise interesting instructional strategies and actions. Only a selection of these simulation learning environments are discussed in this section.

'Smithtown' (Shute & Glaser, 1990; Shute, Glaser, & Raghavan, 1989) is an intelligent tutoring system and can be characterized as a simulation learning environment. It was designed to accomplish two goals:

- enhancing an individual's general problem solving and scientific inquiry skills;
- learning the principles of microeconomics, especially the law of demand and supply.

Smithtown allows students to manipulate variables freely, observe the effects, and apply on-line tools. These tools are:

- a notebook for collecting data from experiments;
- a graph utility to plot data;
- a hypothesis menu to formulate relationships among variables;
- history windows showing chronological listing of all actions, data, and concepts.

Smithtown recognizes two types of systematic investigations. First, explorations in which learners observe and obtain information to generate hypotheses about the domain. The system does not provide coaching in exploratory mode. Second, experiments which are actions that are conducted to confirm or differentiate hypotheses. Experiments are associated with specific predictions from a prediction menu.

To design instructional support, good and ineffective inquiry behaviour of students was determined and coded into rules describing these types of behaviour. Then actual behaviour of students was monitored and matched against these rules. Subsequently, instruction was given in accordance to the type of behaviour. A list of specific performance measures was created. These learning indicators were extracted from the student history list and ordered by complexity. An example of good inquiry behaviour is: changing one variable at a time while holding everything else constant and conscientiously recording relevant data in the on-line notebook.

Herczeg and Herczeg (1988) developed ELAB, a simulation program for the analysis of electronic circuits. ELAB works together with ELEX, which is an expert system that consists of three subcomponents: a simulation, a laboratory and an electronics expert.

- The simulation expert controls and automatically optimizes the simulation parameters for each simulation run according to a qualitative description of a learner.
- The laboratory expert helps learners while setting up experiments in ELAB. It makes learners aware of unintentional critical situations and mistakes.
- The electronics expert helps learners in building and understanding circuits.

The electronic expert enables learner to solve problems by communication on a more abstract level. To do this it presents textual information on the qualitative and quantitative characteristics of the present circuit. The textual information explains related electronic concepts and relations between variables e.g., give statements about qualitative dependencies between device parameters and characteristic circuit parameters. ELEX behaves like a coach: watching and criticizing learner's actions, interrupting when necessary and giving help on request of the learner.

White and Frederiksen (1987; 1989; 1990) also developed an intelligent simulation learning environment for electrical circuits named QUEST (Qualitative Understanding of Electrical System Troubleshooting). Their basic idea is to let learners explore an electrical circuit by a succession of models.

Models progress from a qualitative (zero order) reasoning model through a first order qualitative model to a quantitative model. This *progressive implementation* of models, together with other instructional options such as explanations about circuit behaviour and a presentation of the problem space, makes several learning and instructional strategies possible. These strategies are: open-ended, problem driven, and example driven explorations.

- *open-ended*
  Learners can explore circuits in an open-ended manner by creating their own problems and asking for explanations when necessary.

- *problem-driven*
  Learners are presented with a sequence of problem solving situations that motivate the need for development of their current model representation. Explanations focus on the differences between learners representations and the desired model.

- *example-driven*
  In this tutorial mode learners can ask for demonstrations of solving example problems and reasoning out loud about the present model. Learners are then given the opportunity to solve similar problems.

The three simulation learning environments presented in this section all show different instruction for learners. Smithtown provided learners with tools for structuring the learning processes, for rearranging data, and for diminishing working memory load. In ELAB learners have a private tutor who coaches the inquiry. QUEST's instruction primarily consisted of the representation of the model.

1.5.4 Types of instructional action

The studies mentioned in the Sections 1.5.1 through 1.5.3 present a number of interesting means of instruction. What is missing is a coherent instructional theory that describes the instructional strategies and actions for a simulation learning environment. Reigeluth and Schwartz (1989) presented an instructional theory for the design of computer-based simulations. They focused on the instructional environment of simulations which, until recently, was a strongly underestimated aspect of simulations (van Berkum & de Jong, 1991). Reigeluth and Schwartz (1989) presented three stages in learning. They claimed that these stages contain the features which are important for an instructional theory. These stages are acquisition of the content, application of the content, and assessment of learning. For the acquisition stage they came up with two instructional modes: expository and discovery approach. For the other two stages Reigeluth and Schwartz (1989) presented a number of instructional actions such as the use of natural feedback to maximize the reality of the simulation. In some cases they referred to conditions for these actions, but overall their instructional theory did not describe the conditions under which the instructional actions were valid. Consequently, their theory does not (yet) form a basis for designing instructional support for simulation learning environments.

The sources that were studied in the present section did not show a coherent view which could result in an instructional theory. However, they provide a range of instructional actions which can be categorized in types of instruction. Two dimensions have been distinguished. These dimensions can be recognized in the examples mentioned in the previous sections.

The first dimension deals with the directiveness of the instruction. Instruction to learners can be given in basically two ways: *directive* and *non-directive* (Gick, 1985; de Jong, 1991). Directive measures guide the learner into a certain direction and, in this way, can take away some of the basic freedom a learner has in exploratory environments. Examples are providing hints in ELAB/ELEX (Herczeg & Herczeg, 1988) and progressive implementation of complexity of models in QUEST (White & Frederiksen, 1987). An extensive survey of directive measures is given by van Berkum and de Jong (1991). Non-directive measures do not guide learners in a specific direction but help them in activities they intend to perform themselves. Examples are cognitive tools (Jonassen, 1992) and learner instruments (de Jong, 1991) such as a hypothesis menu (Shute & Glaser, 1990).

The second dimension is *obligatory - nonobligatory* (van Berkum, 1991). Instructional measures can be imposed upon learners whereas a different approach could be to leave the control over use of instructional measures in the hands of learners. This dimension is related to the issue of *learner-control* versus *program-control*. Learner-control does not only have to be concerned with navigation through and operation of a program. It can also refer to learner's control in instruction.

In this thesis the concept of *instructional support* will be used instead of instruction, to emphasize that, for simulation learning environments, instruction also consists of non-directive and nonobligatory measures. Adequate support needs to find the balance between the extremes of the two dimensions. In the

Chapters 4 and 5 more specific types of instructional support for computer simulations will be discussed.

1.6 Research questions

In the current chapter the theoretical background of this thesis was given. Exploratory learning with computer simulations is placed in a broader context of learning processes in general, contemporary learning theories, and instructional strategies that go with them. The main objective of the present chapter was to give a general description of the field of research into which the studies of this thesis can be placed.

It seems that exploratory learning with computer simulations has several advantages as a means of instruction. However, what appears to be missing is insight into the learning processes that are implicated in exploratory learning. Insight into exploratory learning processes is useful for estimating potential problems and for designing effective instructional support. Therefore, the studies in this thesis will focus on the exploratory learning processes and instructional support for exploratory learning with computer simulations. More detailed theoretical background on exploratory learning processes and instructional support for specific processes will be given in the Chapters 3, 4, and 5.

In sum, the research questions of this thesis are:

- What are the learning processes that are implicated in exploratory learning?

- What is the result of instructional support, which is specifically designed to support exploratory learning processes, on learning outcome and the quantity and quality of the learning processes?

To answer the first question, two empirical studies were conducted which will be reported in Chapter 3. The second research question is addressed in the Chapters 4 and 5. In these chapters two experimental studies will be reported that evaluate instructional support measures for exploratory learning.

CHAPTER 2

EDUCATIONAL CONTEXT FOR STUDIES

All studies in this thesis were conducted within the regular curriculum of the Department of Mechanical Engineering of Eindhoven University of Technology. The choice to perform the studies in regular curricula limited the possibilities for implementing experimental conditions but increased the relevance of findings. The educational context of the four studies is introduced in the present chapter. First, the domain of the educational context, namely control theory, is explained briefly. Students in this domain worked with a computer simulation in a computer lab. This simulation program is described as well as the way in which students worked with the simulation in the computer lab.

2.1 Domain: control theory

The domain involved in the present studies is *control theory*, a subdomain of mechanical engineering. Control theory is specifically appropriate for exploratory learning with simulations because it is a complex domain with multivariate and dynamic relations and, therefore, provides clear experimentation possibilities. Key concepts in the domain are: Laplace transform fundamentals, frequency domain analysis, and time domain characteristics.

The primary goal of the domain is to control (models of) mechanical systems. A mechanical system can consist of a combination of masses, dampers, and springs. Systems are controlled by means of a *controller* i.e., a control device of which the control law can be altered. Problems that can be addressed are e.g., damping of vehicles and servo problems. In the studies presented in this thesis the controllers are determined by three actions or a combination thereof:

- a proportional action;
- a differential action;
- an integrating action.

In general, a proportional action influences the speed of the response of a system, a differential action influences the stability of a system, and an integrating action influences steady state error.

Figure 2.1 depicts a global overview of the model used in the domain.

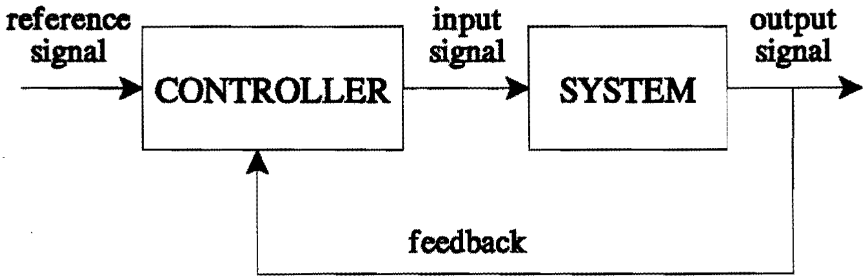


Figure 2.1 General model used in control theory.

The controller influences the relations between the input and output signals of the system. Examples of input and output signals are displacement, velocity, and acceleration of defined masses. The purpose of the control device is to obtain optimal functioning of the system where 'optimal' is dependent of:

- preferences of the controller (in this case the controller is the person who controls the system and not the control device);
- prescribed or mechanical requirements;
- physical limitations of the system.

2.2 Simulation program: PCMatlab

In the educational context of the studies in this thesis students worked with a simulation program *PCMatlab* (© Mathworks) for the domain of control theory. Originally, PCMatlab was not developed for educational purposes but it is intended for scientific and engineering numeric calculations and graphics. It can be considered as a program for complex numeric calculations or as a design tool for constructing and operating simulations of systems. Furthermore, it can be used for e.g., linear algebra, matrix calculations, and digital signal processing.

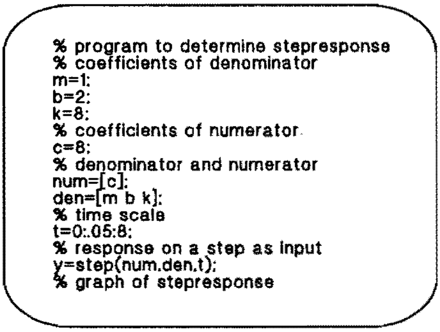
For control theory, PCMatlab offers students a range of standard functions. Input for control systems is given by differential equations, which represent specifications of a mechanical system and the control law. When the mechanical system is modelled, students do not make any changes in that part of the model. The only input given by students is the control law. Output can consist of two-dimensional graphs of variables, which describe the relations between reference signal, input signal and output signal, as a function of time. In comparison to traditional instruction in control theory, the use of PCMatlab made it possible for students to investigate mechanical systems with a higher complexity level. In Figure 2.2 an example is given of input data assembled in a standard input data file and an output screen given by PCMatlab.

2.3 Computer lab

Control theory is taught as a second and third year course as part of the compulsory curriculum for mechanical engineering students at Eindhoven University of Technology. The course consists of lectures, an instruction, and a computer lab, given in a parallel fashion. The lectures offer theoretical background concerning control theory and serve as a foundation for the computer lab. Preceding the computer lab, students receive an instruction (3.5 hours). The instruction intends to be an intermediate between the theory and the practical application of the theory in the computer lab. During the instruction students are informed about the application of rules and methods. The instruction does not involve the operation of the simulation program PCMatlab. In general, students had prior experiences with PCMatlab in their first year of study.

The computer lab consists of one session (3.5 hours) a week for a period of four 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 or three tutors available. The educational goals of the computer lab are:

- to acquire conceptual and procedural knowledge of control theory;
- to acquire procedural knowledge of PCMatlab.



```
% program to determine stepresponse
% coefficients of denominator
m=1;
b=2;
k=8;
% coefficients of numerator
c=8;
% denominator and numerator
num=[c];
den=[m b k];
% time scale
t=0:.05:8;
% response on a step as input
y=step(num.den.t);
% graph of stepresponse
```

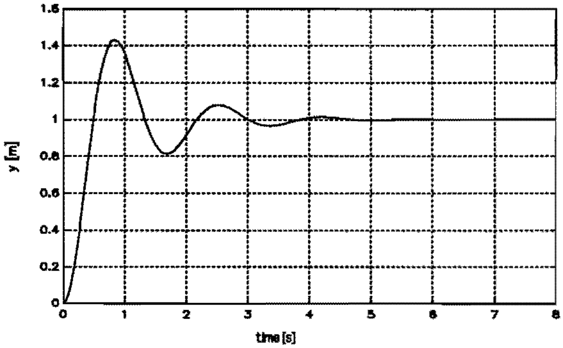


Figure 2.2 Example of input data and output screen given bij PCMatlab.

2.3.1 Organization of the computer lab

The organization of the computer lab was slightly different for each of the four studies and differences are discussed in the present section.

Study 1

For Study 1 the organization of the computer lab was as follows. For each of the four lab sessions students received an assignment which had to be carried out with the simulation program. The assignment did not only define the system to control but also guided the students with study questions. The study questions were meant as a step-by-step guidance towards the correct solutions of an assignment. Students had to hand in a written report of the fourth and final assignment. This report was discussed with their teacher as an assessment of students' performance in the computer lab.

Study 2 and Study 3

Partly as a result of findings of Study 1 (see Section 3.2) the Department of Mechanical Engineering had changed the organization of the computer lab. This altered organization was introduced for the Studies 2 and 3. The basic idea of the changes was that the two goals of the computer lab, control theory as well as PCMatlab, were explicitly acknowledged and the relation between the two goals was stressed explicitly. At the start of the computer lab, PCMatlab operations were explained in general, without explicit emphasis on control theory. The first session of the computer lab started with the calculation of simple models. These calculations could still be done by hand. Gradually more complex models were introduced that required PCMatlab for calculating these models. Therefore, some PCMatlab operations were presented together with short exercises to practice the syntax. Thus, the importance of the simulation program was illustrated and the PCMatlab operations were gradually introduced and practised. The second and third session offered the students the opportunity to increase experiences by employing PCMatlab operations in assignments related to control theory. These assignments were meant as an exercise, offering a model to explore, study questions to answer, and problems to solve. The assignments were not specifically aimed at the stimulation of exploratory behaviour: they described a mechanical system, suggested the students which control laws to use and even which values for the parameters in the control law to apply. The fourth and final session of the lab was used as the experimental session and the organization of this fourth session will be discussed in further detail in the Sections 3.3 and 4.3.

Study 4

For Study 4 a slightly different organization was chosen. In order to prepare students in the experimental groups for the experimental session, part of the experimental support measures were already introduced to these students in the third session of the computer lab (for details see Section 5.2). Thus, students in the experimental groups could get used to the new way of learning before the effect on learning processes and learning outcome was measured.

2.3.2 Assignments

In general, assignments that are given to students in the computer lab require students to analyze the system, in terms of stability or steady state error of the system, and the control problem. Hereafter, students have to determine which controller is required to control the system and which of the tools have to be used to set the parameters of the controller optimally. Some of the tools, which can be applied by students, are impulse response, step response, position of the poles, Bode plot, and Nyquist plot. Each tool has its own discernable characteristics e.g., output of a step response gives information about steady state error and rise time. An example of an assignment is a servo problem: determine the trajectory of an object such as a chisel which has to follow a certain path to generate a pattern.

CHAPTER 3

EXPLORATORY LEARNING PROCESSES

In Chapter 1 three research areas (problem solving, discovery learning, and learning by induction) were used to gain insight into exploratory learning. Salient aspects of these research areas were combined into a preliminary concept of exploratory learning. The present chapter addresses a critical question that was not adequately answered after analysis of the literature in Chapter 1. This question is the first research question of this thesis: What are the learning processes implicated in exploratory learning? At the start of the studies in this thesis, there was no comprehensive list of exploratory learning processes. To answer this research question, two empirical studies were conducted and these studies are reported in this chapter.

Literature on learning from computer simulation that is reported in Section 3.1 is limited to research that was used as input for Study 1 and will show that at the time of Study 1 the exploratory learning processes were only partly identified. During and after the Studies 1 and 2, more literature appeared that was directly concerned with exploratory learning processes. At the end of this chapter results of the empirical studies and recent literature is combined into an inventory of exploratory learning processes.

3.1 Orientation on exploratory learning processes with computer simulations

DeNike (1976) reported that most studies on learning with computer simulations were concerned with the impact of computer simulations in terms of factual knowledge, motivation, and attitudes. Also, later studies on learning with computer simulations (e.g., Coote, Crookall, & Saunders, 1985; Min, 1987; Smith & Pollard, 1986) did not deal with exploratory learning processes but were concerned with the application of computer simulations in education and effects of this means of instruction on learning outcome.

More recent studies on computer simulations focused on the effects of simulations on learners' exploratory abilities and skills. These abilities and skills formed a basis for insight into exploratory learning processes. Rivers and Vockell (1987) studied the impact of computer simulations on scientific problem solving of high-school biology students. Results of this study showed that computer simulations helped students to increase their problem solving abilities substantially. Rivers and Vockell (1987) argued that students who are using computers simulations have more opportunities for active, reinforced practice to help them develop generalized skills. Further, they concluded that transfer of knowledge and problem solving strategies to other situations was an important outcome of learning with computer simulations. The results of this study imply that *generalizing* is a significant exploratory learning process.

Lavoie and Good (1988) studied high-school students working with a computer simulation in biology. They focused on learners' prediction skills. Learners who were successful in predicting were compared to learners who were unsuccessful in these skills. Successful learners tended, for example (Lavoie & Good, 1988, p. 344-5):

- to predict how a given independent variable would relate to a given dependent variable;
- to test the relationship and then judge the predictive success;
- to plan future actions.

From the skills that Lavoie and Good (1988) mentioned, several learning processes were derived such as, *predicting*, *testing*, *evaluating*, and *planning*.

The processes that were gathered from these two studies from literature did not result in a comprehensive inventory of exploratory learning processes. Therefore, further empirical research was required.

3.2 Study 1: Charting exploratory learning processes

In the present study a first overview is given of the exploratory learning processes. This overview is based on a number of thinking aloud protocols of students working with a simulation program in a computer lab. The simulation program was discussed in Chapter 2 that also described the educational context.

Further, it should be stressed that Study 1 has an introductory and descriptive character.

3.2.1 Research set-up

Subjects
Subjects were eight third-year mechanical engineering students working in pairs. The four pairs of subjects were selected at random from students who followed the computer lab. Subjects participated in the experiment on a voluntary basis. They received no credit points or financial compensation for their participation.

Research setting
Subjects worked with a simulation program PCMatlab (© Mathworks) in a computer lab for the domain control theory. The fourth and final session of the lab was used as the research setting. Subjects received an assignment that defined a system that they had to control. Furthermore, the assignment provided exercises and study questions. Subjects were asked to verbalize their thinking processes aloud and these verbal protocols were recorded.

When subjects encountered problems they could ask assistance of a tutor. The tutor was a member of the regular team of tutors for the computer lab but was given directions on the instructional actions that were allowed in the experimental setting e.g., the tutor should stimulate subjects to find the answers themselves.

The research setting tried to imitate the original educational context as closely as possible (for details on the educational context, see Chapter 2). In particular, the assignment that students received in the research setting was identical to the one used in the original setting. Furthermore, subjects were allowed to work in pairs. However, for experimental control two aspects were different from the original context. First, each pair of subjects worked in a separate room. Second, the tutor was in another room and was called for whenever subjects asked for assistance. This was done to make sure that subjects' verbalizations did not influence the tutor's actions. Moreover, subjects were now urged to try to solve their problems themselves.

Thinking-aloud protocols (Ericsson & Simon, 1984) were used to gather data. Furthermore, log-files (on-line registrations of subjects' input and program output) and the notes subjects made were collected. In order to study tutor-subject interactions, the tutor was asked to write down his idea of the subjects' problem, and the reason why he gave the answer he had given. In sum, the data gathered are:

- subjects' thinking aloud protocols;
- tutor's notes;
- subjects' notes;
- on-line logfiles.

The last two sources were used to supplement the analysis of the protocols.

Subjects' thinking aloud protocols were transcribed and analyzed. A scheme was developed for analyzing the protocols and this scheme is discussed in the next section. Analysis was done in cooperation with a domain expert to make sure that domain-related reflections of the subjects would be properly interpreted. The same method was used in Ferguson-Hessler and de Jong (1990) where a high (convergent) validity was obtained and a similar approach was applied in de Jong and Ferguson-Hessler (1991) where an interrater reliability of 88% was achieved.

In analyzing the protocols, no distinction was made between the verbalizations of either subject within each pair. Therefore, a pair of subjects was the unit of analysis. Miyaki (1986) considered thinking aloud in pairs a solution to the unnatural aspect of the traditional research situation. When subjects are working in pairs, they are not forced to talk aloud in a situation in which they would normally be silent. Miyaki (1986) labelled this new experimental method for gathering verbal reports 'constructive interaction'.

3.2.2 Results

Analysis scheme for exploratory learning processes

An analysis scheme was developed to classify the learning processes. The procedure to create this scheme was as follows: on the basis of research on problem solving (Ferguson-Hessler, 1989; Mettes & Gerritsma, 1986), study processes (Ferguson-Hessler & de Jong, 1990) and specific studies on working with computer simulations (Lavoie & Good, 1988; Rivers & Vockell, 1987) an outline for an initial scheme was made.

Initial versions of the scheme were put to the test with parts of the protocols, resulting in several modifications and alterations. This was done in an iterative process and each time the processes in the scheme were defined and classified more precisely e.g., testing was divided into *manipulating* and *interpreting of output*. Moreover, iterative development of the analysis scheme resulted in criteria for identifying learning processes in the protocols. For example, for the process 'model exploration' criteria were distinguished such as referring to variables or parameters and reporting relations between variables. Finally, iterative development resulted in the analysis scheme for Study 1 with twelve exploratory learning processes (see Table 3.1).

Learning processes can be described at different levels. Shute, Glaser, and Raghavan (1989) for example made use of 'learning indicators', which are descriptions of learning processes, that stay closely to behaviours or activities. In Chapter 1 learning processes were defined as significant combinations of cognitive functions but some of the processes from Table 3.1 do come close to the level of activities.

Table 3.1

Analysis scheme of processes for Study 1

	Process	Definition
1.	**Looking for and/or finding of information**	On the basis of a detected deficiency of information, looking and/or finding of information in memory or books.
2.	**Planning**	To devise a scheme/outline for exploring the simulation.
3.	**Conversion**	To convert information e.g., reading, making notes.
4.	**Model exploration**	To (qualitatively/quantitatively) examine the model relations and making the relations within the model explicit.
5.	**Predicting**	To give a (qualitative/quantitative) prediction of the outcomes.
6.	**Manipulating**	To handle, control or change the (values of the) variables or parameters.
7.	**Interpreting**	To give one's understanding of the meaning of output on a conceptual level, without referencing to explicit model relations. Interpreting can be done by comparing with other known graphs or data.
8.	**Verifying**	To control or check the accuracy or correctness beyond the syntax level.
9.	**Evaluating**	To determine the significance of results.
10.	**Generalizing**	To draw, infer or induce general principles or inferences.
11.	**PCMatlab-operations**	Processes for the operation of PCMatlab.
12.	**General**	General and off-task processing.

This scheme was used for analysis of all the protocols including the parts of the protocols that were used to develop the scheme.

Learning processes

The protocols were transcribed and analyzed with the use of the scheme. In each protocol verbalizations or clusters of verbalizations of a pair of subjects were classified as one learning process from the scheme and frequencies of learning processes for each protocol were determined. There was a large variation in the total numbers of processes engaged in by a pair[2]. Table 3.2 presents the relative frequencies.

Table 3.2

Relative frequencies of the learning processes per subject pair

	Subject pair				
Process	1	2	3	4	*M*
Looking/finding information	.14	.21	.24	.21	.20
Planning	.09	.09	.05	.06	.07
Conversion	.03	.06	.05	.04	.05
Model exploration	.04	<.01	.02	.03	.02
Predicting	.02	<.01	<.01	<.01	.01
Manipulating	.01	.01	.02	.01	.01
Interpreting output	.15	.05	.02	.07	.07
Verifying	.05	.02	.09	.05	.05
Evaluating	.05	.04	.03	.03	.03
Generalizing	<.01	.00	.00	<.01	<.01
PCMatlab-operations	.40	.46	.48	.45	.45
Off-task	.02	.05	.01	.04	.03

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[2] The lowest number of processes engaged in by a pair was 326, the highest 524. The mean was 445.

Additional analysis of some of the processes was done to acquire more detailed insight. This additional analysis resulted in a number of observations:

- 20% of the learning processes were processes in which subjects searched for extra information. Further analysis showed that subjects especially searched for domain-specific information.

- 7% of the learning processes were planning processes but when planning was done, subjects tended to plan on short intervals i.e., planning had a short span of control and was only concerned with the next or next few processes. Subjects hardly made overall strategic plans with relevance to a substantial combination of processes. Moreover, subjects usually failed to plan but just tried different approaches without a specific purpose in mind.

- The process 'conversion' was involved in 5% of the learning processes. It appeared that in the process of 'conversion' subjects frequently made notes. However, examination of subjects' notes showed that their descriptions did not give an impression of the exploratory processes but only reported the answers to the lab assignment.

- For two processes the attribute qualitative or quantitative was determined. For the process 'model exploration' it showed that subjects explored the variables or parameters in the model in 2% of the processes and that subjects only stated qualitative relations. As was the case with model exploration, the process 'predicting' was only done on a qualitative basis. Furthermore, analysis showed that subjects only predicted after some output was given by the simulation program.

- In 1% of the processes subjects manipulated variables or parameters of the model. For the process 'manipulating' further results are reported in the section on tutor-subjects interactions.

- In 7% of the processes subjects interpreted output. Further analysis showed that subjects mostly compared output with other known graphs or data such as output from previous assignments, or graphs or data familiar from books or lectures.

- Verification was involved in 5% of the subjects' processes and it appeared that this process was mostly concerned with verification of the input and not of the output.

- Evaluations were done in 3% of the processes. It showed that subjects partly evaluated after interpreting the output but also evaluated without making an interpretation. When subjects failed to interpret the output but did evaluate, they just stated that the output was correct the moment it appeared on the screen and continued with the rest of the assignment. Further analysis showed that in more than half of the evaluations subjects evaluated the output and not the solution strategy.

Additionally, overall study of the protocols showed that processes did not appear in a sequential order but seem to appear iteratively. Especially, processes such as 'looking and finding of information' and 'planning' occurred throughout the session.

Questions for help and tutorial actions
In analyzing subjects' requests for help, it appeared that subjects needed a large amount of extra information, especially domain knowledge. The four pairs of subjects together had 24 tutor-subjects interactions and 30% of these interactions were concerned with domain-dependent questions. Furthermore, subjects seemed to have trouble with the interpretation of graphs and data. In 25% of the interactions subjects asked for help on interpreting output. Subjects also had difficulties with manipulating parameters. They were reluctant to choose values for the parameters according to their preferences.

The tutor did not act as a lecturer but tried to stimulate the subjects to find the answers themselves (e.g., by asking questions, by relating findings to the model or simply by referring to a quotation in the textbook). With regard to the process 'interpreting output' subjects mostly wanted feedback on results they had obtained. In some cases the subjects questioned the correctness of the output but in other cases they failed to understand the meaning of graphs or data. When subjects asked for help on the interpretation of output the tutor gave feedback and suggestions to make subjects find out for themselves. The questions referring to the manipulation of parameters related to the procedure to be followed. In general, procedural difficulties as well as difficulties in manipulating parameters made subjects feel totally lost. Subjects hoped the tutor would explain the next operation they could execute. These procedural difficulties were merely discussed in relation to domain knowledge. When subjects had difficulties with manipulating parameters, the tutor had to emphasize that the subjects could choose the values for the parameters according to their preferences but did not suggest any manipulations or values for parameters. In sum, the tutor presented a diverse range of tutorial actions including explaining, giving feedback, asking questions and hinting.

3.2.3 **Conclusions**

Evaluation of the analysis scheme

As was stated in Section 3.1, studies identifying learning processes that take place when learners are learning with a computer simulation were initially sparse. The analysis scheme presented in Study 1 was a first attempt to create a more comprehensive list. In general, the scheme did provide a list of more detailed exploratory learning processes. Processes could be identified in the protocols and the relative frequencies of processes of the subjects gave an impression of the way students learned with a simulation program. Furthermore, potential problems could be identified and described in terms of learning processes. Finally, it appeared that, although processes in the scheme are presented in a sequential order, they occurred iteratively during learning.

Improvement of the scheme is necessary to separate classes of learning processes. The analysis scheme of Study 1 mainly contained processes of information transformation. One of the exceptions is the process 'planning' that has a regulatory function. For the sake of clearness and to prevent interference between classes of processes a next version of the analysis scheme should distinguish between functions of learning processes. In Study 2 the scheme of the present study is adjusted and the new version of the scheme is empirically tested.

Learning processes of subjects

It appeared that subjects in the present study did not have sufficient domain-dependent knowledge for exploratory learning with the simulation program and had to look for this information or ask for the tutor's assistance. The importance of domain knowledge in using a computer simulation has been emphasized by others. According to Hartley (1988) knowledge provides a guiding framework for exploratory learning. The study of Lavoie and Good (1988) also showed that students who were successful in predicting, generally had high initial knowledge of subject matter.

Lavoie and Good (1988) presented other processes that were significant for successful predictions, such as making notes. According to Lavoie and Good (1988) making notes was important because it facilitated identification of relations between variables by allowing comparisons to be made among several computer runs without having to rely on memory. In the present study however, the subjects had to hand in a report for their assessment. Therefore, the notes they made were used for this report and probably not used as a reminder for themselves.

In the domain of control theory model exploration is a significant process because a model in this domain consists of two parts. The first part represents a mechanical system and the second part represents a controller. For control theory extensive analysis of both parts of a model is required. As the data in the present study showed subjects seldomly used the process 'model exploration'. At some points in the assignment it was preferable to make the relations explicit in the part of the mechanical system and at other points in the assignment it was important to relate the control device to the rest of the model. White and Frederiksen (1987) differentiated between qualitative and quantitative models. The same separation was used to describe the explorations that were done by subjects in the present study. Results showed that, although the model presented in the assignment was described and manipulated in a quantitative way, the subjects only stated qualitative model relations. The assumption that subjects in this study mainly regarded the model qualitatively was strengthened by the qualitative character of the predictions.

Furthermore, subjects seemed to have trouble with manipulating variables and parameters in the model and could not handle the exploratory freedom they were allowed. The tutor had to draw the subjects attention to the fact that they could actually choose the values of the parameters according to their preferences. Knowing this, the subjects only manipulated as much as the assignment asked them to do. Contrary to what might be expected (Bork & Robson, 1972) subjects showed no initiative at this point.

In the present study, subjects also seemed to have trouble with the interpretation of output and sometimes requested help on the meaning of graphs. Output interpretation is very important because learners are using visual pattern recognition facilities e.g., to see trends (McKenzie & Padilla, 1984), relating variables, and verifying their nature (Mokros & Tinker, 1987). The fact that subjects sometimes just stated that output was correct without further analysis of the output was disappointing. These results combined with the low frequencies for the process 'model exploration' made it obvious that subjects probably did not work with a general idea about the model that guided their processes. Furthermore, subjects also hardly made generalizations. In the present domain it is possible to generalize output of the simulation program by relating the output to other mechanical models. Perhaps because the assignment did not invite the subjects to do so, they failed to generalize.

Although operating PCMatlab is one of the educational goals of the computer lab, an average of 45% of the total number of processes is a fairly high percentage. As the program was originally not developed for educational purposes but for industrial usage, its user interface is not geared towards students. A lack of sufficient practical experience with PCMatlab hindered most of the subjects. Some subjects were so engrossed in the operation of PCMatlab and the correction of syntax errors that the primary goal of the computer lab was neglected.

A general conclusion of analysis of subjects' learning processes is that processes characteristic for working with simulations e.g., model exploration, predicting, interpreting output, and generalizing were not used extensively. Furthermore, processes relating to control of the learning processes e.g., planning and verifying, were not used frequently. Additionally, requests for help were also related to these processes e.g., tutor's help was required with interpreting output. Thus, it appeared that subjects did not learn with the simulation program in a true exploratory manner. Subjects certainly did not profit from this simulation maximally, had many difficulties in working with the simulation program, and needed additional domain knowledge. These results imply that subjects did not work with an analytic but with a 'try-and-see' approach. Notable is that in the present study results are troubled by the fact that a major part of subjects' processes were taken up by the operation of PCMatlab. However, if the scores on these processes for operation of the simulation program were withdrawn to regard the results of the other learning processes, proportions between scores on the other learning processes would be identical. In Study 2 the organization of the lab was changed to prevent strong emphasis on the operation of the simulation program and learners' exploratory processes are studied with a revised version of the analysis scheme.

3.3 Study 2: Classes of exploratory learning processes

The aim of Study 2 was twofold. The first aim was to tune the analysis scheme of exploratory learning processes. The second aim was to evaluate guidance that consisted of hints on the use of specific learning processes. The main reason for introducing these hints was that in Study 1 subjects working with a simulation program in a computer lab did not behave as explorers and were reluctant to use specific exploratory learning processes. Expectations of Study 2 were that the group that received hints would show a higher use of exploratory learning processes.

For Study 2 the organization of the four sessions of the computer lab as it was used in Study 1 was altered. In the present study PCMatlab operations were gradually introduced and practised in the first three sessions before experimental measures were taken in the fourth session.

3.3.1 Experimental set-up

Subjects

Subjects were 17 second-year mechanical engineering students, working in pairs. The eight pairs (one "pair" consisted of 3 students) of subjects were selected at random from students who followed the computer lab. Subjects participated in the experiment on a voluntary basis. Subjects were assigned to one of the two experimental conditions on the basis of the average score on three prior, introductory, courses. Good (scores equal to or higher than 70%) and poor pairs (scores lower than 70%) were distinguished. These groups were evenly assigned to the two conditions.

Procedure

The research setting of the present study was similar to the setting of Study 1. In sum, subjects worked with a simulation program PCMatlab (© Mathworks) in a computer lab for the domain control theory. Research was done in the fourth and final session of the lab. Subjects received an assignment, which defined a system that they had to control, and were provided with exercises and study questions. Subjects were asked to verbalize their thinking processes aloud and these verbal protocols were recorded. When subjects encountered problems they could ask assistance of a tutor.

The research setting resembled the original educational setting (for details on the educational context, see Chapter 2). One adjustment of the original setting was that subjects did not work in the normal computer classroom but each pair of subjects worked in a separate room. The tutor was waiting in another room and was called whenever subjects asked for assistance. In this way, the verbalizations could not influence the tutor's actions and subjects were urged to try to solve problems themselves.

Experimental conditions

In the original educational context and also in the research setting of the previous study, the assignment given to the subjects was not explicitly aimed at provoking an exploratory attitude. In the present study exploratory learning processes are stimulated by hints in the assignment. In Section 1.5.4 a distinction was made between directive and non-directive support. The hints given in the present study can be considered as support of a very directive nature. However, since the assignment was not designed specifically for stimulating exploratory learning the term *guidance* is used for the experimental condition of Study 2. 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 guiding subjects towards an exploratory attitude, by giving suggestions for performing the learning processes hypothesis generation and testing (see Table 3.3 for a description of these processes). Hints were given for hypothesis generation and testing. These processes are crucial exploratory learning processes because by building and testing hypotheses learners acquire knowledge of the domain. An example of a part of the unguided and guided assignment is:

> 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 in the guided assignment may seem quite straightforward, but the style of questioning in the original unguided assignment was also very direct. For the guided version, the assignment was altered on the aspect of content and not on the aspect of style.

Data collection and analysis

Thinking-aloud protocols were used as the main method of research of the exploratory learning processes. Similar to Study 1, other data sources were used to aid analysis of the protocols. These other sources were log-files (on-line registrations of subjects' input and program output), the notes subjects made, and the notes the tutor made about his idea of the subjects' problem.

The same method as in Study 1 was used. A pair of subjects was the unit of analysis. The protocols of the subjects were transcribed and analyzed in cooperation with a domain expert to make sure that domain-related verbalizations of students would be properly interpreted and analyzed. For reasons of efficiency three parts of the assignment were selected beforehand. 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 the control device).

3.3.2 **Results**

Analysis scheme of exploratory learning processes

For the present study the analysis scheme of Study 1 was adjusted on the basis of new literature. Two major adjustments of the analysis scheme of Study 1 were made. First, Reimann (1989) made a distinction between hypothesis generation and prediction and this distinction is used in the analysis scheme for the present study. Secondly, exploratory learning processes at the highest level of the analysis scheme were categorized into classes. Lodewijks (1985) distinguished levels on which research of learning processes can focus. The first level is the transformative level concerning processes that transform (domain-dependent) information into knowledge. On the second level, the regulative level, the processes related to executive control issues are of primary interest. The analysis scheme of Study 2 consists of the following classes:

- transformative processes;
- regulative processes;
- operating the simulation;
- supplementary processes.

Transformative processes are processes that transform domain-dependent or domain-independent information into a learner's knowledge base.

Transformative processes were further 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 interpretations were included. *Regulative processes* refer to executive control of the learning processes. Examples of these regulative processes are planning or monitoring. *Operating the simulation* is concerned with processes for managing PCMatlab. Additionally, processes that consisted of routine operations were scored in the class of *supplementary processes* e.g., making notes by copying data from the screen. The class of supplementary processes was not scored when subjects for example explicated or questioned data during writing but were only used for low level routine processing.

Similar to Study 1, the new version of the analysis scheme was developed through iteratively testing the scheme to parts of the protocols (for details see Section 3.2.2) and resulted in the analysis scheme of Study 2. The complete scheme of 22 processes is given in Table 3.3. Similar to the analysis scheme of Study 1, learning processes are described at different levels i.e., as mental transactions as well as descriptions that stay close to the activity level.

Table 3.3

Analysis scheme of processes for Study 2

TRANSFORMATIVE PROCESSES

Analysis

Search of information and identifying and relating variables and parameters in the model and indicating general properties of the model. This can be done on the basis of prior knowledge, additional material, but of course also at the basis of data from running the simulation.

1.	**Looking for and/or finding of information**	Searching for (missing) information in e.g., text books, additional material.
2.	**Model exploration: identifying**	Identifying the variables, parameters of the model.
3.	**Model exploration: qualitative relation**	Making the relations within the model explicit by identifying qualitative relations.
4.	**Model exploration: quantitative relation**	Making the relations within the model explicit by identifying quantitative relations.

Hypothesis generation

5.	**Hypothesis generation**	Formulating 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

Testing involves those activities that are necessary for gathering data on which the learner expects to be able to accept or refute a new hypothesis, or to create a hypothesis.

6.	**Designing an experiment**	Indicating what will be changed in a simulation model and in which order.
7.	**Predicting (qualitative)**	Stating the expectation of a simulation run outcome as the result of designated value attributions to variables. The expectation is stated in qualitative terms.
8.	**Predicting (quantitative)**	Stating the expectation of a simulation run outcome as the result of designated value attributions to variables. The expectation is stated in quantitative terms.
9.	**Manipulating variables/internal parameter(s)**	Handling, controlling or changing the (values of the) variables or internal parameters which describe system properties.
10.	**Manipulating external parameter(s)**	To handle, control or change the (values of the) external parameters which represent the relation with the environment.

11.	**Interpreting output (local)**	Interpreting output without a direct reference to model relations. The learner can do this in a local manner (noticing specific characteristics of the output, for example: this is an a-symptotic relation).
12.	**Interpreting output (conceptual)**	Giving one's understanding of the meaning of the output on a conceptual level. Conceptual interpreting can be done by comparing with other known graphs or data (output from previous assignments or graphs/data familiar from books/lectures). Also, interpreting output on a conceptual level is done without a direct reference to model relations.
13.	**Supporting output interpretations**	Performing supportive action for interpretation of the output e.g., changing the range on an axis.

Evaluation

14.	**Evaluating/Judging**	Judging one's operations and the results thereof e.g., "I shouldn't have done this experiment.").
15.	**Generalizing**	Putting one's 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**	Indicating an outline for what to do. Planning can be at the level of the complete discovery process, or at the level of one of the phases indicated above.
17.	**Verifying**	Checking correctness of operations and results at a conceptual level (e.g., "Did I use the right parameter ... , let's see.").
18.	**Monitoring**	Observing and keeping track of one's study process (e.g., "So, let's see if we have what we want ...").

PCMATLAB OPERATIONS

19.	**PCMatlab-operations**	Operating the simulation program PCMatlab.

SUPPLEMENTARY PROCESSES

20.	**Calculating**	Performing routine calculations.
21.	**Making notes**	Making notes by copying data from the screen.
22.	**Off-task**	Off task remarks.

Learning processes

Table 3.4 gives the mean percentages of learning processes for the guided and the unguided groups. The processes as depicted in Table 3.4 are processes at the most detailed level of the analysis scheme.

Table 3.4

Mean (M) and standard deviation (SD) of the percentages[3] *of processes of the analysis scheme for the unguided and guided groups*

	Group					
	Unguided (*n*=4)		Guided (*n*=4)		Total (*N*=8)	
Process	*M*	*SD*	*M*	*SD*	*M*	*SD*
Looking/finding information	13.0	6.1	13.5	2.5	13.2	4.3
Model exploration: identifying	0.8	1.7	1.1	0.9	1.0	1.2
Model exploration (qualitative)	3.3	4.2	3.0	1.8	3.1	3.0
Model exploration (quantitative)	0	0	0.3	0.7	0.2	0.5
Hypothesis generation	0	0	0	0	0	0
Designing an experiment	0	0	0	0	0	0
Predicting (qualitative)	1.5	1.3	0.6	0.7	1.0	1.1
Predicting (quantitative)	0.4	0.7	0	0	0.2	0.5
Manipulating var./int. parameters	0	0	0	0	0	0
Manipulating external parameters	0	0	0	0	0	0
Interpreting output (local)	10.0	2.8	6.4	0.6	8.2	2.7
Interpreting output (conceptual)	4.7	1.8	2.7	1.9	3.7	2.0
Supporting output interpretations	1.9	0.7	2.4	2.3	2.1	1.6
Evaluating/Judging	6.5	2.8	8.2	2.5	7.3	2.6
Generalizing	0.4	0.8	0.2	0.4	0.3	0.6
Planning	12.6	5.1	11.4	4.1	12.0	4.3
Verifying	3.4	1.7	3.4	2.1	3.4	1.8
Monitoring	15.9	1.2	18.7	4.4	17.3	3.3
PCMatlab-operations	13.3	3.5	10.1	1.9	11.7	3.1
Calculating	3.8	1.5	6.2	2.9	5.0	2.5
Making notes	5.0	3.2	7.4	1.6	6.2	2.7
Off-task	2.3	3.0	4.8	2.6	3.6	3.0

---

[3] 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.

Additional analysis of some of the processes was done to acquire more detailed insight. Further analysis of the process 'looking for and/or finding of information' showed that subjects mainly needed domain-dependent information. Model explorations were done in 3.1% of the processes but were due to qualitative and not quantitative model explorations. Learning processes paramount to exploratory learning, such as hypothesis generation, designing an experiment, and manipulating variables, were (almost) absent. Interpreting output was done by subjects but they primarily used local interpretation. Evaluating was done by subjects in 7.1% of the processes but generalizing was done in less than 1%.

Results of the regulative processes show that the number of planning processes is 12%. Further analysis showed that subjects tended to use planning on short intervals i.e., planning had a short span of control and was not concerned with an overall strategic plan. Planning mostly related to the more simple processes such as 'supportive processes for interpretation' and 'calculating'. The monitoring process scored 17.3%. However, further analysis of results showed that the monitoring process quite frequently consisted of (re)reading the assignment.

One of the important findings of Study 2 is that there were no significant differences between the guided and unguided groups of subjects on the learning processes (t-tests with $p < .05$).

3.3.3 Conclusions

Evaluation of the analysis scheme

Further development of the analysis scheme of Study 1 resulted in a more detailed overview. The division between hypothesis generation and predicting (Reimann, 1989) was made in the analysis scheme but results of Study 2 could not provide an empirical confirmation, simply because hypothesis generation was not used by subjects. Furthermore, the division of processes into classes gave good insight into the function of exploratory learning processes. Especially, the division between transformative and regulative processes appeared useful for analysis of exploratory learning processes. By separating regulative processes from the transformative ones, regulative processes were acknowledged as processes of a different class that require research from a different perspective. The focus in the present study was mainly on the transformative processes. A research question aimed at regulation of learning processes will probably require a more detailed class of regulative processes and some of the processes that are now in the transformative class can be judged and renamed for their regulative impact.

For the scheme to become an inventory of learning processes one important adjustment is necessary. The present scheme also includes learner activities e.g., manipulating. These activities were included for a complete overview but are not relevant for the inventory because manipulating itself does not imply cognitive processes. Before a learner can manipulate, cognitive processes are required to decide which variable or parameter to manipulate but this is part of the process 'designing an experiment'. Therefore, activities such as manipulating should not be part of a conclusive inventory of exploratory learning processes.

Learning processes of the subjects

First of all, it was found that learning processes that are important for exploratory learning (such as hypothesis generation, designing an experiment, manipulating variables) were (almost) absent. This is in line with the results of Study 1. Subjects were reluctant to make use of the exploratory learning processes and did not exploit the simulation program maximally. The assignment did not invite subjects to explore freely and subjects are apparently not used to exploratory learning as an instructional strategy. Secondly, results showed that, similar to Study 1, the subjects' need for extra (domain) information was quite high.

In the present study regulative processes were addressed in more detail than in Study 1. Results of the present study showed that the regulative process 'planning' was done in 12% of the processes. This is quite high, especially if this is compared to a nonexploratory environment as learning with text (de Jong & Njoo, 1992). Also, a remarkable high percentage was found for the monitoring process (17.3%). However, planning as well as monitoring were not done profoundly e.g., planning was done on short intervals and monitoring processes consisted of (re)reading the assignment.

Finally, when the division between the main classes in Table 3.4 is examined, the balance between the classes appears to be acceptable. In the previous study subjects used an average of 45% of the processes on the operation of PCMatlab. In the present study an average of approximately 12% was used. Apparently, as a result of the reorganization of the computer lab (see Section 2.3.1), the PCMatlab-operations took up a lower percentage of the total number of processes than in the previous study.

A comparison of exploratory learning processes for the guided and unguided group showed no differences between groups on the learning processes. The general conclusion from Study 2 is that providing the learners with hints was not sufficient for stimulating them in applying exploratory learning processes. Learners were reluctant to use exploratory learning processes and the introduction of hints clearly failed to stimulate exploratory learning. The hints were nonobligatory but did have a directive character. A possible explanation is that the assignment and study questions together with directive hints did not provide learners with a true exploratory environment and even restricted the exploratory freedom of learners. Therefore, in Chapter 4 learners will be provided with an open assignment with instructional measures that are specifically designed to encourage and support exploratory learning.

3.4 Conclusive inventory of exploratory learning processes

During the period when the Studies 1 and 2 were carried out, a number of studies appeared that also addressed exploratory learning processes. Moreover, at the time of publication of this thesis exploratory learning processes are still subject of research. In the present section these recent studies are discussed and related to findings of Studies 1 and 2. As a result, a conclusive inventory of exploratory learning processes is presented that is used as the overview of exploratory learning processes in the remaining two studies of this thesis.

Reimann (1989) observed learners in an explorative learning task with a computer simulation REFRACT for the field of optical refraction. The task required incremental building and testing of hypotheses. Reimann (1989) described the following processes:

- testing and modifying hypotheses;
- designing an experiment;
- making a prediction;
- evaluating the prediction;
- evaluating the hypotheses.

Reimann (1989) specified the difference between hypothesis generation and predicting. In his view a hypothesis is a descriptive generalization of a set of observations and a prediction results from applying a hypothesis to a particular experiment with specific design constraints. A single hypothesis can thus account for several predictions.

One comment on this study is that Reimann's (1989) definition of a hypothesis seems limited. In my opinion it is possible to formulate a hypothesis without any observations from experiments. Perhaps, 'observations' should not be interpreted as 'observe from output of experiments' but should be interpreted as model explorations. This contrast between exploring and experimenting is also made by Shute and Glaser (1990). They distinguished two types of systematic investigations. The first type they labelled 'explorations'. When learners are exploring, they are observing and obtaining information in order to generate hypotheses about the domain. The second type was labelled 'experiments', which consist of actions that are conducted to confirm or differentiate hypotheses. It should be stressed that the concept of 'explorations' as used in model explorations indicates model inquiries and does not apply to 'exploring' as is used in the concept of 'exploratory learning'.

Friedler, Nachmias, and Linn (1990) studied high-school students in a course on physical science. They mentioned exploratory learning processes which resemble the transformative processes in the analysis scheme of Study 2. These processes are:

- define a problem;
- state a hypothesis;
- design an experiment;
- make predictions on the basis of results of previous experiment(s);
- observe, collect, analyze, and interpret data.

Friedler, Nachmias, and Linn (1990) further explained the processes of observation and prediction. The process of observation should make students aware of the variables in the experiment. Prediction was marked as an important process because it causes integration of new information into learner's existing body of knowledge. One of the differences between the two processes is that during observation all variables in the problem space (Newell & Simon, 1972) should be regarded, while during prediction the problem space should be limited.

Klahr and Dunbar (1988) studied learners in an artificial domain. Based on this study Klahr and Dunbar (1988) presented a model of exploratory learning which they labelled Scientific Discovery as Dual Search (SDDS). Although

SDDS was mainly concerned with the structures of this model of scientific discovery and did not specifically address learning processes, it provided a framework for understanding exploratory learning. The fundamental assumption of SDDS is that scientific discovery requires search in two related problem spaces:

- *Hypothesis space*
  The space that represents all possible hypotheses distinguished by characteristic attributes. Search in the hypothesis space is guided both by prior knowledge and experimental results.

- *Experiment space*
  The space that represents all experiments that can be conducted within an informative value range of characteristic attributes. Search in the experiment space can be guided by a current hypothesis and may be used to generate information for the formulation of subsequent hypotheses.

The SDDS model resembles Simon and Lea's (1974, see Section 1.2.4) unified view of problem solving and induction. Simon and Lea (1974) introduced a space of instances and a space of rules. The space of instances is similar to Klahr and Dunbar's (1988) experiment space and the space of rules is similar to Klahr and Dunbar's (1988) hypothesis space. The general notion of both models is that learners should move between the two spaces. Exploratory learning processes take place within one of the spaces or facilitates movements between hypothesis space and experiment space. By stating hypotheses and testing these hypotheses by experiments a learner acquires understanding of the model and domain at hand.

Starting point for the final inventory of exploratory learning processes is the analysis scheme of Study 2 combined with Klahr and Dunbar's (1988) SDDS model and Reimann's (1989) and Friedler, Nachmias, and Linn's (1990) findings. Compared to the analysis scheme of Study 2 a few alterations were made. First of all, learner activities e.g., looking for and/or finding of information and manipulating are excluded. These activities were included in the analysis scheme for a complete overview but are too detailed to be part of the final inventory of exploratory learning processes (see Section 3.3.3). Secondly, regulative processes, such as planning and monitoring, are not included. Regulative processes require further research that is specifically aimed at these processes. Therefore, the inventory only focuses on the transformative processes. Finally, detailed distinctions that do not deal with the function of the process but deal with the application of the process are combined into one process e.g., predicting qualitatively and quantitatively are combined.

It has to be emphasized that the inventory is intended to be descriptive. It is not meant to give a prescriptive approach, which would indicate a relation between learning processes and instructional goals and would prescribe a normative classification of learning processes. Table 3.5 gives the conclusive inventory of exploratory learning processes.

Table 3.5

Inventory of exploratory learning processes

Model exploration	Identifying and relating variables and parameters in the model and indicating general properties of the model. This can be done on the basis of prior knowledge or additional material.
Hypothesis generation	Formulating a relation between one or more variables and parameters in the simulation model. A hypothesis is stated with the intention of testing it.
Designing an experiment	Indicating the (values of the) variables and/or parameters which will be changed.
Predicting	Stating an expectation of the outcome of an experiment.
Interpreting output	Interpreting the output without a direct reference to model relations. Learners can do this in a local manner (noticing specific characteristics of the output, for example: this is an a-symptotic relation) or at a conceptual level by comparing output to other output that is known or to information from other sources.
Evaluating	Judging results of processes and an experiment in order to reject or confirm a current hypothesis.
Generalizing	Inducing general principles by integrating processes and results in the broader context of the domain at hand.

Processes in the inventory of exploratory learning processes were also mentioned in other studies. First, model exploration, which is often referred to as orientation or definition of a problem, is mentioned in literature on problem solving (Mettes & Gerritsma, 1986) as well as literature on learning with computer simulations (Friedler, Nachmias, & Linn, 1990). Secondly, hypothesis generation is addressed by several authors (Friedler, Nachmias, & Linn, 1990; Klahr & Dunbar, 1988; Reimann, 1989; Shute & Glaser, 1990). Thus, although in Study 2 subjects did not make use of this process, literature provided significant results to include hypothesis generation in the inventory. This also holds for designing an experiment, which was not used by subjects in Study 2 but was mentioned in literature by the same authors. The process of predicting was a main topic in studies by Lavoie and Good (1988), Reimann (1989), and Friedler, Nachmias, and Linn (1990). Furthermore, other processes in the inventory were mentioned by only one study in literature. Interpreting output was only mentioned by Friedler, Nachmias, and Linn (1990), evaluating was only mentioned by Reimann (1989) in relation to predictions and hypotheses, and generalizing was only mentioned by Rivers and Vockell (1987). Klahr and Dunbar's (1988) SDDS model provided the overall structure to combine all exploratory processes because movements between a space of hypotheses and a space of experiments require exploratory learning processes.

Processes in the inventory can be used to evaluate exploratory learning, to define potential problems, and to serve as a framework for designing instructional support. Studies in this thesis concentrate on the use of the inventory for these purposes. However, future studies could go one step further than categorizing separate learning processes and categorize exploratory strategies. At present, the processes in the inventory are not meant to occur sequentially but should be considered as processes that can occur iteratively. In future research, processes from the inventory could be used to describe exploratory strategies. Further research of literature already revealed that in general, exploratory learning allows for two approaches. Greeno and Simon (1984) have described these two approaches in inductive learning and identified them as the top-down and bottom-up methods of inductive inquiry. A similar distinction has been made by Klahr and Dunbar (1988) who distinguished *theorists* or *experimenters*. Theorists search the hypothesis space and only conduct experiments to test the stated hypothesis. Experimenters are recognized by the attribute that they conduct experiments without an explicit hypothesis. Thus, theorists and experimenters diverge in the way they search for new hypotheses once an initial hypothesis is abandoned: theorists search the hypothesis space for new hypotheses, experimenters search the experiment space to see if they can induce some regularities from experimental outcomes. Experimenters also conduct more experiments than the theorists and the experiments are conducted without an explicit hypothesis statement.

Shute and Glaser (1990) have made an analogous distinction between hypothesis-driven and data-driven explorations and results of their study support the superiority of the former approach. They found that subjects who worked hypothesis-driven were more successful. Successful subjects e.g., employed more powerful heuristics and explored in a more systematical way. Less successful learners generally worked data-driven instead of hypothesis-driven. This means that these less successful learners showed no higher level planning in designing and executing experiments and were not able to go beyond a local description of the situation. They failed to conceive lawful regularities and general principles which hold for a class of events rather than for a local description. Their investigation behaviour was impulsive and not systematic e.g., they made impulsive generalizations based on inadequate data and changed more multiple variables simultaneously.

In the present chapter the importance of the exploratory learning processes has been emphasized. Especially hypothesis generation is significant, since by accepting and rejecting hypotheses the learner's mental model of a domain is built. Results of Studies 1 and 2 showed that the processes of stating and testing hypotheses (which includes establishing a link between hypothesis and experiment space) is not an easy task. Learners in these studies did not exploit the simulation program maximally. Instructional support might improve this situation if it is specifically designed to support the exploratory learning processes. In Chapter 4 instructional support measures will be studied that are based on the inventory of exploratory learning processes and especially the process of hypothesis generation will be supported.

CHAPTER 4

INSTRUCTIONAL SUPPORT FOR EXPLORATORY LEARNING PROCESSES

Learning with computer simulations presumes the use of exploratory learning processes as distinguished in Chapter 3. Results of the Studies 1 and 2 showed that some of the most important exploratory learning processes were not or not frequently used by subjects in these studies. To improve the effects of learning with computer simulations, both in learning processes and in learning outcome, learners should be supported in performing the exploratory learning processes.

The first section of the present chapter describes examples of support for exploratory learning processes. Also, attention is given to support for one of the learning processes 'hypothesis generation'. In Section 4.3 an experimental study is reported which evaluates specific instructional support measures. These instructional measures were specifically designed to support exploratory learning processes.

4.1 Supporting exploratory learning processes

In a study by Rivers and Vockell (1987) learners were encouraged to apply exploratory learning with a computer simulation for the domain of biology. They used two conditions in their study: guided discovery and unguided discovery. The guided group received instructional support which consisted of a mixture of concept definitions, propositions about relationships between entities in the model, and suggestions of a more strategic nature. This resulted in statements about the definition of terms used in the simulation, relationships in the model, and strategies for hypothesis testing. Examples of these statements are (Rivers & Vockell, 1987, p. 407):

> The population of the predator and prey are interrelated. A change in one generally has an effect on the other.
> It is a good idea to change only one variable at a time.
> Use this program to test your hypotheses.
> Look for patterns or relationships as you systematically change the variables.

The guidance was supplied at a controlled pace as part of the computer program and learners could not bypass its presentation. Learners were permitted to re-examine previous screens upon request. An accompanying student manual provided study questions and problems to solve.

Results of this study showed that learners using the guided version developed skills in critical thinking and scientific thinking processes more effectively than those using the unguided version.

Rivers and Vockell (1987) combined different types of support. Other studies were concerned with one or two specific learning processes. Friedler, Nachmias, and Linn (1990) studied learners working with a computer-based laboratory especially designed to develop learners' scientific reasoning skills. In their study they provided one experimental group with specific instructional forms about the observation process and another group with forms about the prediction process. On the observation forms the importance of careful observation was stressed. Learners who received the observation forms were given directions to report all details of the experimental set-up, sketch this set-up, and report outcome of experiments. Their attention was directed to noting the relationships between experiments and graphs. Additionally, the observation group also received instruction about the differences between observations and inferences. On the prediction forms learners received instruction to state predictions before starting an experiment and to justify these predictions. Learners who received the prediction forms had to compare their prediction with the actual outcome afterwards.

Results of this study showed that learners in both conditions improved on domain-dependent knowledge and the ability to use other scientific reasoning skills to solve problems such as the ability to control variables and plan an experiment. Differences between the conditions were found on the specific processes that were supported. The observation group became better observers e.g., they scored a higher number of relevant details. The prediction group became better predictors, although they did not achieve complete mastery of this process.

Reimann (1991) designed an interactive simulation environment called REFRACT about optical refraction. REFRACT is especially designed to stimulate learners' processes of hypothesis generation and testing. However, support was particularly given for testing and not for generating hypotheses. Emphasis was given to the process of prediction. Learners had to predict the outcome before feedback of the simulation program was given. Furthermore, the degree of precision of prediction could be varied according to the student's knowledge and preferences. Predictions could be stated in a numerical or graphical manner. Feedback was also given in these two different manners. Learners could ask for numerical aspects of an experiment and numerical and nominal values of variables could be stored into a Notebook. Table options in the Notebook were: sort values, select experiments, enter equation, and replay.

In general, learners working with REFRACT did not find the important generalizations and showed considerable individual differences with respect to the knowledge acquired during exploratory learning. Furthermore, learners developed preferences for a certain degree of precision of predictions. Two successful learners made use of a specific procedure when making predictions. They started with an imprecise prediction and then improved precision of the prediction. Learners did not exclusively use quantitative information about variables and often did not identify promising variables.

The studies presented in this section illustrate that support for exploratory learning can address general exploratory strategies, as well as one of the exploratory learning processes from the inventory of Chapter 3. Supporting exploratory learning processes in the presented studies mainly resulted in improvement of the performance of these exploratory processes.

4.2 Supporting hypothesis generation

In Chapter 3 the importance of hypothesis generation was stressed because by accepting and rejecting hypotheses the learner's mental model of the domain is built. The studies in Chapter 3 showed that subjects did not generate hypotheses. Several other studies tried to support learners in creating hypotheses and these studies are reported in this section.

Smithtown, a simulation for the domain of microeconomics (e.g., Shute & Glaser, 1990) offered the learner support for hypothesis generation by a hypothesis menu. This menu consisted of:

- a connector window which included the items: 'if', 'then', 'as', 'when', 'and', and 'the';
- an object window which included the variables of the domain at hand;
- a verb window which included types of change such as: 'decreases', 'increases', 'shift as a result of';
- a direct object window which could be used for obtaining precise specification of concepts.

Supporting learners to encourage the use of scientific inquiry with the hypothesis menu resulted in more efficient acquisition of domain-dependent knowledge. A group of learners working with Smithtown was compared to a group that received classroom instruction. It showed that classroom instruction was less efficient than learning with Smithtown. Results showed that the Smithtown group achieved similar results in less time than the group that received classroom instruction.

Van Joolingen and de Jong (1991; 1993) made use of a similar principle in what they labelled *hypothesis scratchpads*. Here, learners were offered different windows for selecting variables, relations and conditions. Hypotheses that were created could be placed on a 'hypotheses list' and be marked as 'under study', 'false', 'true' and 'unknown'. By setting the variables to be included in a hypothesis and by determining the moment at which hypotheses could be entered (before or during sets of simulation runs) van Joolingen and de Jong (1993) influenced the exploratory behaviour of learners.

All these studies offered learners elements of hypotheses that they had to assemble themselves. A more directive support for creating hypotheses can be found in CIRCSIM-TUTOR (Kim, Evens, Michael, & Rovick, 1989), an Intelligent Tutoring System in the domain of medicine which treats problems associated with blood pressure. In CIRCSIM learners were posed with a perturbation of the cardiovascular system, for example: 'the atrial resistance is decreased to 50% of normal'. Subsequently they were asked to predict what would happen to seven components of the cardiovascular system. This prediction had to be made in a qualitative way (increase, decrease, steady) for three different moments in time. To be able to write down this prediction learners were offered a 7 (components) x 3 (moments in time) spreadsheet. In CIRCSIM-TUTOR the program took the lead in choosing both input and output variables for the learner, and in determining one part (the change in the input variable). This study on CIRCSIM-TUTOR did not address effects of the support measures on exploratory learning.

Offering learners complete hypotheses to explore leaves even less exploratory freedom for learners. In PPT (Pathophysiology Tutor; Michael, Haque, Rovick, & Evens, 1989) learners could choose a predefined hypothesis by using a list of nested menus that each give a more specific fixed list of hypotheses in the field of physiopathology. Michael et al. (1989) did not study the effects of PPT on learning outcome and learning processes.

The instructional support measures in the present section introduced different levels of directive instructional measures. The least directive measure that was mentioned is just prompting the learner to state a hypothesis (van Joolingen & de Jong, 1991). More direction is given when learners were offered hypothesis scratchpads (Shute & Glaser, 1990; Shute, Glaser, & Raghavan, 1989) and this has even more direction when the variables on the scratchpad were pre-selected and manipulated by the researcher (van Joolingen & de Jong, 1993). Choosing from lists of predefined hypotheses is still more directive (Michael et al., 1989).

The study reported in the following section evaluated instructional measures designed to support learners in the exploratory learning processes from the inventory of Chapter 3. Specific attention is given to the process of hypothesis generation. In the previous Sections 4.1 and 4.2 studies were discussed that also supported hypothesis generation and some of the other exploratory learning processes. Supporting exploratory processes in these studies resulted in efficient learning and appeared to improve exploratory learning processes. Study 2 of this thesis guided learners in exploratory learning by providing hints in a guided assignment. Results of Study 2 showed no differences between the guided group and a control group. Just hinting learners to perform exploratory learning processes is not an adequate instructional measure. In the present chapter learners are not hinted in a guided assignment but are given an open assignment, which challenges them to learn in a true exploratory manner. Additionally, learners are provided with instructional measures that specifically support exploratory learning processes.

4.3 Study 3: Instructional measures to support exploratory learning

The experimental groups in Study 3 were placed in a setting that was specifically designed to stimulate exploratory learning (see also Chapter 2 for details on the educational context). For instance, learners were given an assignment that triggered initiative and free activity. Subjects were also given specific instructional support for exploratory learning processes. Support consisted of an *information sheet* and *fill-in forms*, with or without hypotheses. Effects of these support measures on the quantity and quality of the learning processes and learning outcome were studied.

4.3.1 Experimental set-up

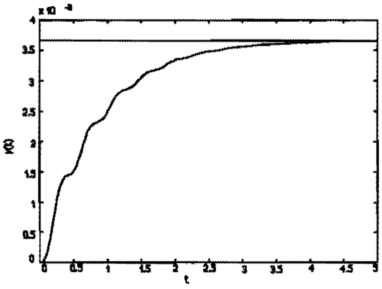
Subjects
Subjects in Study 3 were 91 second-year mechanical engineering students. Subjects worked in pairs and this resulted in 44 pairs (some "pairs" consisted of three students). Four experimental groups (*n* is 7 to 10 pairs of subjects) and a control group of 10 pairs participated.

General procedure
The control group followed the simulation lab with a directed assignment like the ones used in Study 2 and received no additional support. All subjects in the experimental groups received:

- specifications of a model of a system (a ship that had to be kept on course);
- an open-ended assignment to explore the model with the aim of constructing the optimal regulation for the system. It was stressed 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. The subjects were informed 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;
- additional support in the form of an information sheet and fill-in forms. Different variants of the information sheet and fill-in forms were designed. Experimental groups differed in the specific combination they received (see the next section).

All groups completed 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 4.1.

The graph is a step response of a third order system. 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 4.1 Posttest item of Study 3.

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 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 labelled VARIABLES & PARAMETERS, HYPOTHESIS, EXPERIMENT, PREDICTION, DATA INTERPRETATION, and CONCLUSION. Each of the cells contains an exploratory learning process as identified in Chapter 3. Two processes, evaluating and generalizing, are combined in one cell namely CONCLUSION. The size was 42 x 30 cm (16.5 x 11.8 in.). Figure 4.2 gives an impression of the structure of the sheet and forms.

The cells of the information sheet contained information on the six exploratory learning processes. Two variants of the information sheet were designed. In one variant we only offered *general information* about the six learning processes.

In the other variant, learners were not only provided with this general information, but additionally with *domain-specific information* on the processes.

VARIABLES & PARAMETERS	HYPOTHESIS	DATA INTERPRETATION
EXPERIMENT	PREDICTION	CONCLUSION

Figure 4.2. Example of structure of sheet and forms.

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 it's Laplace transformation A(s); ...

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

- forms that had only blank cells with the six labels (*free fill-in forms*);
- 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 were 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 were provided are:

  With a proportional control law you cannot influence the stability of the system.
  The value of the feedback amplification K influences the sub- or supercritical damping of the system.

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

- General - Free ($n = 7$ pairs);
- General - Hypotheses ($n = 10$ pairs);
- Domain specific - Free ($n = 8$ pairs);
- Domain specific - Hypotheses ($n = 9$ pairs).

The experimental groups (that were existing computer lab groups) were assigned to the conditions on 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. Figure 4.3 gives an overview of the experimental setting.

Data collection and analysis

In the Studies 1 and 2 thinking-aloud protocols were used to assess learners' exploratory learning processes. These verbal protocols offered a high level of detail that was necessary for gaining insight into exploratory learning processes but is not required for evaluation of the instructional support measures. For assessing the effects of the different instructional support measures on exploratory learning, the statements that the subjects noted on the fill-in forms

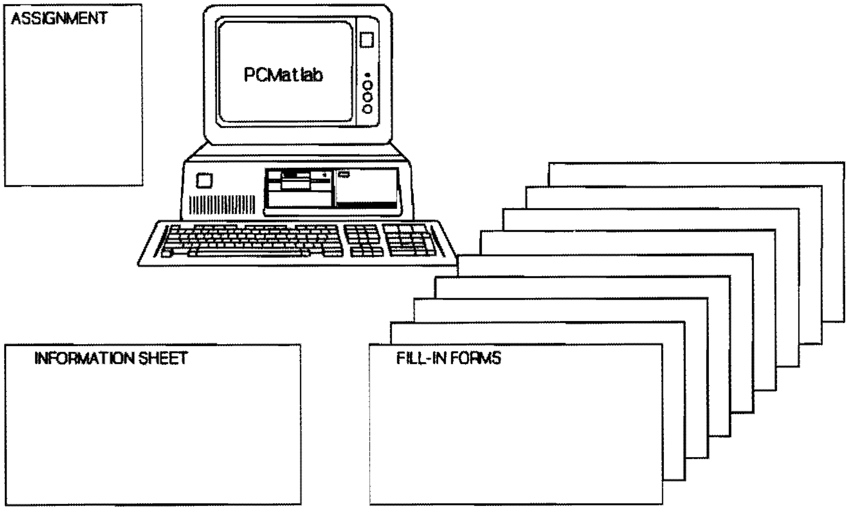


Figure 4.3 Experimental setting.

were analyzed. Analysis was performed in a stepwise order by introducing five 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, Glaser, and Raghavan (1989). The five levels of analysis give an indication of the quality of the learning processes. The assessment of the quality of the learning processes was chosen, instead of other aspects such as sequence of learning processes or time spend on a specific learning process, because it provides significant information for evaluation of the support measures.

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. In Appendix A these aspects are described in detail. At the third level the *domain correctness* was determined. Only the aspects of the statements that had proven to be valid at the previous level were analyzed at the third level. The fourth level was labelled the *consistency* level and was an assessment of the relations between contents of different cells on one fill-in form. The fifth and final 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). Since these scores on each level are related to scores on the previous level, relative scores were used. 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). Table 4.1 gives an overview of the levels of analysis.

Table 4.1

Analysis levels, data and operationalisation

Level of analysis	*Data*	*Operationalisation*
Global activity assessment of the general activity level of the subjects	• the number of forms • the total number of cells	
Learning process validity assessment of the level in which the statements in each cell answered the general description of the cell (as was given on the information sheets)	• scores per cell • total score	For each cell primary aspects that should be present were determined. For example: in the cell EXPERIMENT subjects could note down the input variables, the output variables, and the values of the input variables (see Appendix A for the other cells). For the six cells on one sheet, a maximum of 20 points could be scored. As only part of the subjects received hypotheses to explore, the cell HYPOTHESIS is analyzed separately from the rest of the data.

Level of analysis	*Data*	*Operationalisation*
Domain correctness assessment of the domain correctness of the statements	• scores per cell • total score	For the primary aspects of the learning process validity level the domain correctness was determined. For example: if the value(s) of the input variable(s) was/were given in an experiment, the domain correctness of this choice was scored. In this example, a mistake would be to give a negative value if the input variable could only have positive values. Of course, subjects could state 'false' hypotheses (in the sense that a hypothesis can be falsified) as well. Therefore, the hypotheses were analyzed separately from the rest of the data.
Consistency assessment of the relations between contents of different cells on one fill-in form	• total score	Only learning process valid and domain correct statements were analyzed at this level. Relations between the statements in the two cells were determined at a global level. For example: are the same variables used in the hypothesis and the experiment. The following relations were evaluated: HYPOTHESIS - EXPERIMENT EXPERIMENT - PREDICTION EXPERIMENT - DATA INTERPRETATION PREDICTICN - DATA INTERPRETATION DATA INTERPRETATION - CONCLUSION The relation HYPOTHESIS - EXPERIMENT was analyzed separately from the rest of the data. Valid but 'false' hypotheses were analyzed at this level.

Level of analysis	*Data*	*Operationalisation*
Overall strategy assessment of the development of the statements in the same cell through different forms	• total score	The development of the successive hypotheses and the relation between a hypothesis and the conclusion on the previous form.

The cell HYPOTHESIS was analyzed separately from the rest of the data for two reasons. First, part of the experimental groups received hypotheses to explore and could, therefore, not be rewarded for "their" hypotheses at the learning process validity level and beyond. Secondly, a hypothesis can be 'false' in domain related sense i.e., can be falsified by an experiment, but can still be a good hypothesis to explore.

4.3.2 **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 taken into account the number of forms this pair had used. In this way a percentage of cells filled-in was calculated. In the calculations it was taken into account that the groups with hypotheses fill-in forms could not fill in the HYPOTHESIS cell.

Table 4.2 shows that overall the subjects used an average of almost 5 fill-in forms. Table 4.3 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 only fill in five cells).

Table 4.2

Mean numbers of forms (standard deviation between parentheses)

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

Table 4.3

Mean percentages of cells filled in (standard deviation between parentheses)

Information sheet	Fill-in forms		
	Free	Hypotheses	Total
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*)

There was a 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 form and the groups with free fill-in forms used 3.7 forms ($F_{(1,30)} = 15.89, p < .01$). The type of information sheet (general or 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 hypotheses 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. Providing subjects with hypotheses forms resulted in higher global activity 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 i.e., 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 the aspects that should be present were determined. 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 form. 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 4.4 gives the learning process validity scores for each of the main experimental conditions separately, so that each pair of subjects' scores are included in the figures twice. This table shows that overall the learning process validity score of subjects was about 42%. The cells VARIABLES & PARAMETERS, EXPERIMENT, and PREDICTION scored 55.4%, 57.2%, and 57%, respectively. Scores in the cell PREDICTION showed a high standard deviation. The cells DATA INTERPRETATION and CONCLUSION scored 24.5% and 25.3%, respectively.

For the cell DATA INTERPRETATION two aspects that were used as criteria for assessing the learning process validity level in this cell were hardly used by subjects. These two aspects were comparison with other graphs/data and discussion about the experiment. In the cell CONCLUSION subjects hardly generalized their findings to other models. Especially the groups with the free fill-in forms did not draw conclusions about the validity of the hypotheses.

The only significant influence of the differences between experimental conditions 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 4.4 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. The groups with domain-specific sheets scored 29.3% in the cell CONCLUSION and the groups with general information sheets 21.4%. 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).

Table 4.4

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*
VARIABLES&PARAMETERS	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 INTERPRETATION	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[4]	41.8	5.2	41.9	9.4	42.0	5.6	41.8	9.6

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 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:

- Statements that could be scored under the description of another cell such as VARIABLES & PARAMETERS, PREDICTION and EXPERIMENT;
- Statements that could not be scored at this level (not relevant, not interpretable);
- 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

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[4] The total learning process validity is not an average of the scores of the five 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).

inquiries of the model. These general model explorations were meant to observe the behaviour 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.

Data presented so far were concerned with statements made in a specific cell. However, it is likely that subjects sometimes made mistakes in placing statements in cells e.g., subjects placed experiments in the cell HYPOTHESIS. In the method of analysis that is chosen, these misplaced statements are not included in the scores. Some of the statements that could not be scored in a certain cell appeared to be misplaced. If these misplaced statements were added to the scores, the total learning process validity of all groups increased from 41.9% to 49.3% (*SD* = 7.4) with a similar trend in separate cell scores. Nevertheless, misplaced statements were not included in the present and the following levels of analysis because this way of scoring required additional interpretation of data.

Domain correctness

For domain correctness only those aspects of the statements were analyzed 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' hypotheses and, therefore, the HYPOTHESIS cell was analyzed separately from the other data. Other learning processes were analyzed in the context of this 'false' hypothesis. 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.

Table 4.5

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*
VARIABLES&PARAMETERS	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 INTERPRETATION	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[5]	83.1	13.4	77.6	11.6	84.5	10.4	75.2	13.7

Overall there is a high score (80.4%) on domain correctness 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 was 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, results showed 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 4.5 also shows that for the total scores for domain correctness there is a similar effect ($F_{(1,30)} = 6.10$, $p < .025$). The scores of the groups with domain-specific information sheets did not differ from the groups with general sheets. However, similar to most of the scores on the previous

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[5] 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.

levels, the group Domain specific-Hypotheses had the highest score on all the cells (scores ranged from 86.6% to 95.4%).

Because subjects stated few hypotheses, the absolute numbers for this cell were considered. 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 the relations between the statements in different cells on one fill-in form were assessed. The following relations were analyzed:

- HYPOTHESIS - EXPERIMENT;
- EXPERIMENT - PREDICTION;
- EXPERIMENT - DATA INTERPRETATION;
- PREDICTION - DATA INTERPRETATION;
- DATA INTERPRETATION - CONCLUSION.

Only those statements were analyzed that were valid at the learning process validity and domain correct. At the domain correctness level aspects (of statements) that were learning process valid were assessed. At this level a number of crucial aspects were looked at and if these were learning process valid the complete statement was included in the consistency analysis. For the cell HYPOTHESIS hypotheses were also analyzed 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. No effects were found 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) the relation HYPOTHESIS - EXPERIMENT was looked at separately. Seventy-one of these relations could be analyzed and only five were assessed as incorrect.

Overall strategy

As a final analysis level an assessment was made of the development of the successive hypotheses and the relation between a hypothesis and the conclusion on the previous form. As was mentioned in the preceding sections, very few statements passed the sieve. Therefore, only some examples are discussed.

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. The following example illustrates the transition:

> 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 added one element to the control law.

All levels of analysis

The overall (over all experimental conditions and all subjects) average scores for each level are depicted in Table 4.6. Results showed that the total score on the learning process validity level was almost 42%, whereas domain correctness and consistency scored 80% and 90%.

As the levels of analysis worked as a sieve it might be possible that aspects of statements that passed the level of learning process validity had a higher chance of being domain correct than parts of statements that did not pass the sieve. In other words, parts of statements that did not pass the sieve of the second level had to be assessed on their domain correctness. When the parts of statements that did not pass the learning process validity level were assessed on their domain correctness it showed that almost 90% was correct.

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 (19) = 2.33, $p < .05$).

Table 4.6

Mean scores (M) and standard deviation (SD) of the total scores (over all conditions, subjects and cells) on each level of analysis

	Total score	
Analysis level[6]	*M*	*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

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[6] At the fifth level of analysis, the overall strategy level, the development of successive hypotheses and the relation between a hypothesis and the conclusion on a previous fill-in form had to be analyzed. Results in the section about the learning process validity level already showed that subjects stated few hypotheses, thus leaving insufficient data for analysis at the fifth, overall strategy, level.

4.3.3 Conclusions

In the present study the impact of instructional support measures on the exploratory learning processes was evaluated. The statements that students made on fill-in forms as they worked with a simulation were analyzed. Analysis was done in a stepwise order. At each level subjects gained scores that expressed a percentage of correctness relative to some maximum score.

Results over all levels of analysis showed that the bottle neck in exploratory learning appears to be 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. This was not caused by the sequence of analysis levels because the parts of statements that did not pass the learning process validity level were generally domain correct.

More specifically, the transformative process 'hypothesis generation' appeared to be a difficult task. Shute and Glaser (1990) concluded that hypothesis generation was one of the most reliable indicators of successful learning with Smithtown. 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 hypothesis-driven approach was the most effective. The most successful subjects concurrently used both approaches.

A related problem for the subjects was the difference between a hypothesis and a prediction. These two processes were frequently mixed up. Further, subjects had considerable trouble with an adequate performance on data interpretation and drawing conclusions. Data interpretation was mostly done at a rather shallow level; subjects scored low on this learning process. In the cell CONCLUSION generalizations were hardly made. Again, Shute and Glaser's (1990) study substantiated that generalizing is an important process and that this process serves as a good predictor for successful performance.

A second major aspect of the present study was the impact of the different instructional support measures that were designed. Although a direct comparison with the results of the Studies 1 and 2 is impossible, results indicated that the instructional support measures together with the open assignment invited subjects in Study 3 to use characteristic exploratory learning processes. This impression was supported by the global activity level (see Table 4.2 and Table 4.3).

Furthermore, within Study 3, 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. In the present study a number of significant effects of the instructional measurements were found. 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 significantly better results on the learning processes. Providing subjects with hypotheses might have caused advantages in other cells e.g., as the hypotheses that were provided were learning process valid subjects could possibly more easily review these hypotheses in the conclusion. Furthermore, at the consistency level of analysis it appeared that if hypotheses were provided, then the design of a matching experiment was not too difficult. However, the general relation between a hypothesis and an experiment as was scored at the consistency level does not say anything about the appropriateness of the experiment.

Although the results of the present study were not conclusive, support of exploratory learning processes showed positive results. Furthermore, literature showed that not only support, but also training of exploratory skills can improve the results of exploratory learning. Shute and Glaser (1990), for example, recommended tutoring on the scientific inquiry skills. Also, Friedler, Nachmias, and Linn (1990) showed successful instruction with prediction and observation forms. Furthermore, recent studies also recommended to relate learner attributes to instructional support (Shute, 1990; 1991) and domain characteristics (Glaser et al., 1992).

An important question is of course: What is the effect on performance tests? Owing to practical reasons the test that was given in Study 3 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 significantly lower score than the control group. Results of recent studies (de Jong, de Hoog, & de Vries, 1993) showed similar results. A possible explanation is that the subjects in this group were more involved in performing the exploratory learning processes than in acquiring domain-specific knowledge. This explanation is supported by results of Study 3 that showed that the Domain specific - Hypotheses group had high scores on most of the levels of analysis.

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 positive results, it is likely that students need to work in this way for a longer period of time, before significant results will appear.

CHAPTER 5

INSTRUCTIONAL SUPPORT BY STRUCTURING THE HYPOTHESIS SPACE

In Chapter 4 several ways of supporting hypothesis generation were discussed. The instructional support measures mentioned differed in the level of being 'directive'. A highly directive measure is giving learners hypotheses to explore. This was done in Study 3 and resulted in higher general activity of learners and higher quality of learning processes e.g., domain correctness of the learning processes. Less directive is to let learners choose from lists of predefined hypotheses (Michael et al., 1989) or provide learners with hypothesis scratchpads that consists of elements of a hypothesis (van Joolingen, 1993; Shute & Glaser, 1990; Shute, Glaser, & Raghavan, 1989).

The study in the present chapter evaluated the option of letting learners choose from a list of predefined hypotheses. Compared to Study 3 the instructional support measure in this chapter increases learners' exploratory freedom but by introducing an overview of hypotheses the aspect of sequencing of the hypotheses in the overview is introduced. In Section 5.1 organizing hypotheses and the possible consequences of different sequences on the exploratory learning processes and learning outcome are addressed. In Section 5.2 an experimental study is reported that explores the effects of different structures of hypotheses that represented different movements in hypothesis space (Klahr & Dunbar, 1988).

5.1 Structuring the sequence of hypotheses

When hypotheses are offered to learners, a choice for a certain sequence should be made. This sequence determines the movement of the learner through the space of possible hypotheses. The sequence of hypotheses is the result of the type or sequence of the *relations* or the *variables* in the hypotheses. For example, following work by White and Frederiksen (1989; 1990) and by Plötzner and Spada (1992) hypotheses could be offered in a qualitative to quantitative sequence. Thus, in these studies, relations are used to guide the sequencing. Another way to sequence hypotheses is to follow variables from the domain. In studies by van Joolingen (1993) and van Joolingen and de Jong (1991) variables from a domain are ordered in a hierarchy, with global variables at the top and specific (instantiated) variables at the bottom.

Apart from this, specific sequences can be followed within one domain by regarding different types of variables. An example of this can be found in Eylon and Reif (1984), who presented a domain from physics in two different structures. One structure followed a historical line of thought, the other structure followed essential concepts from the domain. Their study showed that when a (hierarchical) structure is clearly presented (for example in a graphical way) to learners they tend to internalize this particular structure, which is subsequently reflected in their problem solving abilities.

Moyse (1991) used two different descriptions of the system in the simulation (of a control panel for a nuclear power station) and studied the effect on quality of processing activities. The two variants were a 'structural' and a 'functional' description. The 'structural' description gave learners the elements of the system without the specific manipulations necessary to achieve specific goals. The 'functional' description gave learners the specific goal-action relations e.g. (Moyse, 1991, p. 36):

To increase furnace temperature -> decrease damping or decrease pump speed or both.

Learners had to keep the operating parameters within an acceptable range by controlling three other parameters. This study showed that the two descriptions resulted in different ways of processing the information. The structural description resulted in more causal reasoning because learners had to deduce the relations between goal and action for themselves. The functional description resulted in rule-based reasoning. Although the variable structures of Eylon and Reif (1984) and the system descriptions of Moyse (1991) are not the same as hypotheses, these studies learn that the learning processes can be contextualized by the structure of the presentation of information that is offered to learners. This might also be the case for the presentation of information in the form of hypotheses.

Prior knowledge

Presenting hypotheses to learners working with computer simulations can only support them if the relations offered in the hypotheses can be interpreted by the learners. This implies that learners' prior knowledge will partly determine how they may profit from the hypotheses offered. Moreover, it is generally assumed that in order to profit from an exploratory learning environment pre-requisite knowledge of the domain (and analogous domains) is necessary (Klahr & Dunbar, 1988).

Schauble et al. (1991) assessed the influence of prior knowledge on experimentation strategies and knowledge gains of learners working with a computer simulation on basic electricity (called 'Voltaville'). They found that the quality of the domain knowledge held by learners when starting to work with the laboratory environment positively influenced the knowledge acquired. One of their conclusions was that (Schauble et al., 1991, p. 225):

> Students with more elaborate and sophisticated causal models made more substantial learning gains.

The more sophisticated models of the better learners also appeared to be related to a better performance of exploratory processes. Schauble et al. (1991, p. 229) stated:

> The unsophisticated models appear to encourage students to look for information in the wrong places, to develop misunderstandings about the functioning of components, and to provide misleading clues about how to interpret unexpected results.

Also, learners who started off with sophisticated models tried to explore the simulation or parts of it, as thoroughly as possible, whereas learners with unsophisticated models worked unsystematically, made no generalizations of new findings, and were even unable to remember the discoveries they had been able to make.

Glaser et al. (1992) studied the relation between characteristics of (three different) domains and successful experimentation behaviour. They also looked at the relation of prior knowledge of the learner and the application of certain learning processes e.g., they expected that learners with high prior knowledge would be more active in the search for disconfirming evidence, would have higher confidence in their conclusions as well as their ability to remember and apply the principles they discover, and would be more inclined to check the principles they discover with their own understanding of the domain. They concluded that prior knowledge can be helpful in exploratory behaviour but, also, if prior knowledge contains misconceptions, can be detrimental for discovery learning. If learners have misconceptions or their prior knowledge is only partly correct, it can encourage learners to distort, ignore, or selectively interpret the evidence that they generate.

In the following study, structured overview of hypotheses were evaluated as an instructional measure to support exploratory learning. Two different structures of hypotheses were created by varying the sequence of hypotheses. The two structures represent a practical and a conceptual movement through the hypothesis space. The practical movement is aimed at the solution of a control problem whereas the conceptual movement is intended to stimulate understanding of the fundamental relations in the domain of control theory. It is assumed that learners' learning processes and learning outcome is influenced by the different movements in hypothesis space. As the structures represented two different approaches within the domain at hand, subjects' domain-dependent prior knowledge was assessed in Study 4.

5.2 Study 4: Structured overviews of hypotheses

The main experimental variants in the present study offered predefined hypotheses in different sequences. In Study 3 positive influences were found when learners were offered predefined hypotheses. Subjects provided with hypotheses were more active and made fewer domain-related mistakes in the formulation of their learning processes. Offering predefined hypotheses, however, is a rather directive measure that easily interferes with the constructive nature of the exploratory process. In the present study, therefore, the level of freedom for subjects was increased and subjects were offered an *overview of predefined hypotheses*. In Study 4 the effect of the structure of this overview on the quantity and quality of exploratory learning processes and the learning outcome is studied. Furthermore, prior knowledge of subjects was assessed and regarded in the analysis. For the study in the present section the educational context of Chapter 2 was used.

5.2.1 Experimental set-up

Subjects

Participants were 88 students Mechanical Engineering taking part in a computer lab on control theory. Students in lab groups normally work in pairs and 43 pairs (two "pairs" consisted of three subjects) took part in the present study. Three lab groups were assigned to two experimental groups (15 and 14 pairs per group) and a control group (14 pairs) on a random basis.

The original lab groups consisted of 97 students. Nine students were not included in the experiment for a number of reasons: three students did not take part in the final experimental session, four students did not have the same entrance level for the lab as the other students, and two students did not follow the experimental instructions.

Support

All groups received an open-ended assignment to explore a given modelled system. Additionally, the experimental groups received support consisting of fill-in forms, which were similar for both groups, and one of two variants of an overview of hypotheses.

Fill-in forms

The experimental groups received *fill-in forms* and additional information about the exploratory learning processes on an *information sheet* (see also Study 3). Subjects were requested to work on the assignment with the simulation using the fill-in forms 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 the fill-in forms and information sheet was identical: they were both divided into six cells labelled VARIABLES & PARAMETERS, HYPOTHESIS, EXPERIMENT, PREDICTION, DATA INTERPRETATION, and CONCLUSION. The size was 42 x 30 cm (16.5 x 11.8 inch).

The cells of the information sheet contained information on the six exploratory learning processes. General information was offered about the six learning processes in addition to domain-specific information or examples. For instance:

> ... Designing an experiment involves the following aspects:
> - *Choice of input.*
>   You can choose the variables (t, r(t)) or parameters (K_r, τ_d, τ_i) to vary.
> - *Choice of output ...*

The fill-in forms had only blank cells with the six labels for processes. In the cell HYPOTHESIS they could write down one of the hypotheses that they had to choose from a structured overview of hypotheses. There was no compulsory order of cells on a form and subjects were urged to follow the order they preferred. In this way, subjects could work through the set of fill-in forms.

Structured overviews of hypotheses

Two variants of the *structured overviews of hypotheses* were designed that represent two approaches of the domain at hand:

- The *controller* structure ordered the hypotheses by increasing complexity of the controllers, at the first level. The controllers are determined by three actions or a combination thereof. The actions are: a proportional (P), differential (D), or integral (I) action. These actions make up for four appropriate controllers: P-controller, PD-controller, PI-controller, and PID-controller. The controllers are presented in increasing complexity with the exception of the PD- and PI-controller which are of equal complexity. At the second level of the structure the theoretical concepts were introduced.
- The *concept* structure ordered the hypotheses by theoretical concepts, at the first level. The two concepts are stability and steady state error. These concepts are two important characteristics of system behaviour. The two concepts were presented in a hierarchical order. At the second level of the structure the four controllers were used.

The structures of the overviews are presented in Figure 5.1.

For each combination of controller and concept, a hypothesis was given concerning the relationship between the parameters of the controller and the behaviour of the system. For each structure the same hypotheses were used in terms of variables and parameters and the relation between them. Each structure included eight hypotheses.

As a result of the two structures, the overviews differed in the order of hypotheses and in the formulation of these hypotheses. Differences in formulation reflected different points of view. In the controller structure the point of view was the controller, whereas in the concept structure the point of

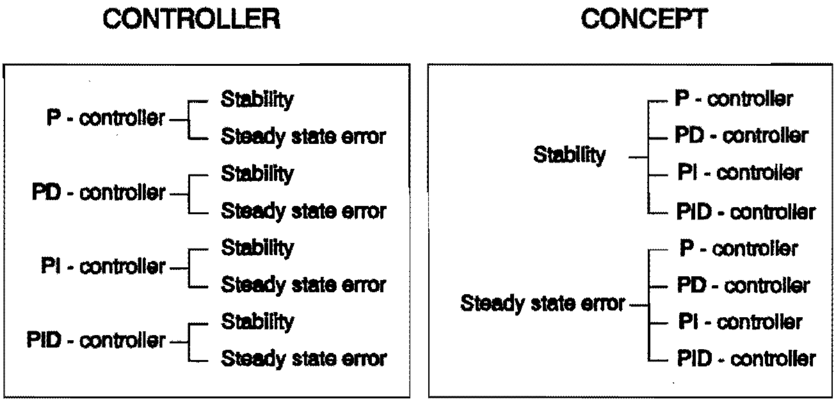

Figure 5.1 Structured overviews for the hypotheses.

view was the behaviour of the system that had to be controlled. An example of a hypothesis formulated differently for both overviews is:

CONTROLLER: By adding a proportional controller the steady state error can be eliminated[7].

CONCEPT: The steady state error can be eliminated by the implementation of a proportional controller.

Furthermore, the hypotheses were stated in an affirmative or a negative sense; five of the hypotheses presented were true and three hypotheses were false.

In Study 3 it appeared that subjects could fill in an average of five forms in one lab session. Since subjects had to follow the structure of the overviews, they were given two rules for choosing hypotheses from the overviews.

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[7] For the system in the assignment this hypothesis is false because the system is not stable. This implies that discussing the problem of eliminating steady state error is redundant. In general, the D-action controls the stability of the system and the P-action controls the steady state error.

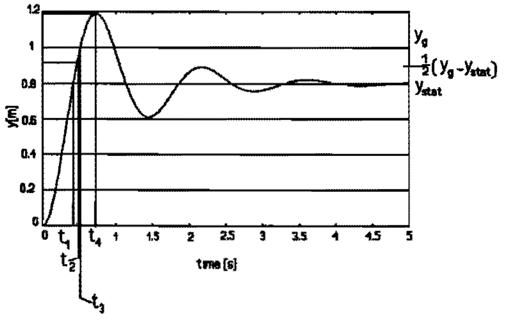
- Subjects had to follow the sequence of the overview. They could skip a hypothesis but they had to move through the overview of hypotheses from top to bottom and could not move upwards again.
- Subjects had to explore a minimum number of hypotheses per section. For the controller overview they had to explore one hypothesis per controller. For the concept structure they had to choose two hypotheses per concept.

Tests

Subjects' prior domain knowledge was assessed using a multiple-choice test (18 items with four alternatives). Items dealt with topics such as damping, feedback and rise time. An example of a test item is given in Figure 5.2.

At the end of the lab session subjects completed a posttest, which consisted of 18 multiple-choice questions with four alternatives, that tested qualitative insight with questions on fundamental aspects of the domain such as analysis of problems situations, relating concepts and controllers, and specifying values for parameters of the controller. An example of an item of the posttest is given in Figure 5.3.

The stepresponse of a second order system in time is shown in the following graph. Which point in time is known as rise time?[8]



a) rise time is t_1
b) rise time is t_2
c) rise time is t_3
d) rise time is t_4

Figure 5.2 Item of prior knowledge test.

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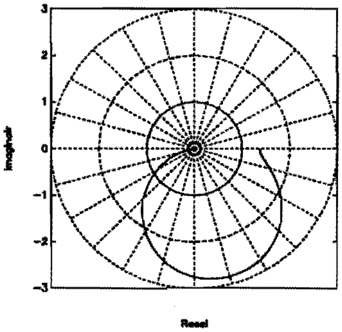
[8] The correct answer is c. The rise time is defined as the point in time when the response of the system first reaches the desired end value (y_g).

A closed loop with a proportional controller shows the following Nyquist plot (closed loop amplification as a function of frequency):

To improve the stability of the regulated system you could consider[9]:



a) nothing, system behaviour will be good.
b) add an I-action.
c) add a D-action.
d) add a D- and an I-action.

Figure 5.3 Example of posttest item.

Experimental procedure

The study was performed in the context of a second year course at Eindhoven University of Technology. The course consisted of lectures and a computer lab. During the lab subjects worked in fixed pairs with self-selected partners. Usually approximately 10 to 20 pairs work in a classroom at the same time. Two tutors per lab group were present to answer any domain- and simulation-related questions. Tutors received special instruction for the experimental situation e.g., how to respond to questions about the fill-in forms or the overview of hypotheses.

The lab took up 14 hours divided into four sessions (Session 1 through 4). Session 1 and 2 were the same for all lab groups. The support measures were used in Sessions 3 and 4. Data were gathered at Session 4.

Session 1 and 2: practice PCMatlab

In the beginning of the first two sessions of the computer lab, PCMatlab operations were explained in a general sense without too much emphasis on control theory. Subjects could practice PCMatlab by working on simple

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[9] The correct answer is c. To avoid a steady state error the amplitude of the closed loop amplification needs to have an infinite value for small frequencies. This is obtained by an I-action. The D-action gives the closed loop amplification an extra phase-shift of 45° for high frequencies. This is needed to satisfy certain control criteria (amplitude-margin).

problems. Gradually, the relevance of PCMatlab for the course in control theory was stressed and subjects received assignments, which put more emphasis on the domain.

These two sessions were the same for the experimental groups and the control group.

Session 3: practice of fill-in forms

At this point, subjects were expected to have mastered a sufficient level of experience with the domain and the simulation program. Therefore, this session was used to let subjects from the experimental groups practice with the support measures. As a basis, subjects were offered a total of three systems that they had to regulate. These situations were of a moderate level of difficulty, since the appropriate control device was already given for each of the modelled systems. Subjects were introduced (both with written and oral instructions) to the fill-in forms with an additional information sheet about the learning processes. For each of the three systems presented they were offered one predefined hypothesis that was meant to help them explore the system. They were explicitly informed 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 with the support of hypotheses, sheet and forms. Both experimental groups received the same situations and hypotheses.

The control group received exercises with some study questions, dealing with the same problem situations as the experimental groups, but did not receive support or hypotheses.

Session 4: conclusive assignment

At the fourth session subjects received an assignment that was the concluding and evaluative stage of the lab. The session started with a written and an oral instruction to explain the procedure. Subjects of all groups had the same amount of time to work on the assignment.

All subjects received specifications of a model and an open-ended assignment to explore this model. The final goal was to construct an optimal controller for the system. The system was an object with a certain mass that should be moved from an initial position to an end position. The influence of gravity was present but friction was not considered. An imperfect actuator[10] that could apply a force to the object was available.

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[10] The actuator should be modelled as a first order system with a time constant and a static amplification.

The subjects in the experimental groups received the support measures that consisted of the fill-in forms, which they had practised to work with in the third lab session, and one of the variants of the overviews of hypotheses. They were familiar with exploring with the help of hypotheses but the structured overview was new to them. They were again informed that this assignment required free exploration and experimenting. It was also emphasized that their explorations did not necessarily have to involve an optimal controller but could also involve less optimal controllers. Subjects were informed that the explorations of other (non-optimal) controllers could result in more general insight of the system and that this insight could help them to explain their final choice. They had to give their final choice for the type of controller with their motivation and the values for the parameters on a separate sheet.

The control group followed the simulation lab with the assignment and no additional support. Table 5.1 summarizes the experimental set-up.

Table 5.1

Elements of the experimental set-up for each group

Group	Test for prior knowledge	Assign-ment	Fill-in forms & information sheet	Controller overview of hypotheses	Concept overview of hypotheses	Posttest
Controller	x	x	x	x		x
Concept	x	x	x		x	x
Control	x	x				x

Data collection and analysis

In this study the performance of subjects on the quality and quantity of the learning processes and learning outcome was assessed.

For assessing the effects of the overview conditions on the exploratory learning processes, subjects' statements on the fill-in forms were analyzed. The analysis was performed in a stepwise order by introducing five levels of analysis (see also Study 3).

The first level is the *global activity* level which is an assessment of the general activity level of the subjects. Global activity indicators are the number of forms, the number of hypotheses 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 the general description of the cell as was given on the information sheet. At the third level the *domain correctness* of the aspects of the statements that had proven to be learning process valid at the previous level was determined. The fourth level was labelled the *consistency* level and was an assessment of the relations between contents of different cells at one fill-in form. For the relation between the cells EXPERIMENT and HYPOTHESIS the consistency was analyzed in a more detailed way than in Study 3, for example, the type of experiment that was used was determined. The fifth and final level was called the *overall strategy* level and was an evaluation of the development of ideas through the stack of fill-in forms. This was determined by subjects' choices from the overview of hypotheses and the path through the set of hypotheses offered.

The general idea behind introducing 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. Since these scores on each level are related to the scores on the previous level, relative scores were used e.g., scores on the learning process validity level are related to the maximum score the subjects could have achieved, given the number of cells they had used (and which was scored on the previous global activity level).

Expectations

The following research predictions with regard to the scores on the posttest were formulated:

- Students receiving support will perform better on a posttest than students who have to work with the simulation without support.

- Students' level of prior knowledge will influence the posttest scores i.e., if the level of prior knowledge (as measured with a test for prior knowledge) increases then the posttest score also increases.

- Students receiving hypotheses in a structure that follows the general concepts of the domain will score higher on the posttest than students who receive the hypotheses structured according to the controllers. The idea is that these general concepts address more fundamental aspects of the domain as compared to the types of controllers.

- The effect that students who receive the 'concept' structure of hypotheses perform better than students receiving the 'controller' structure will be more profound for the students with high prior knowledge as compared to the ones with low prior knowledge. The idea is that the structure according to fundamental concepts will be more in line with the knowledge of students with high prior knowledge.

For the two experimental groups the learning processes were assessed by analyzing the fill-in forms that the students used. These learning processes are seen as the intermediate between experimental condition and learning outcome. It was expected that:

- Compared to the other groups of students, students with high prior knowledge and using the structured overview following fundamental concepts will demonstrate exploratory learning processes of a higher quality as will be measured with the four analysis levels.

5.2.2 Results

Test for prior knowledge

The overall mean score on the test for prior knowledge, which consisted of 18 items, was 8.3 (*SD* = 2.4). The group with the controller overview scored a mean of 8.0 (*SD* = 2.9), the group with the concept overview had a mean score of 8.8 (*SD* = 2.3), and the control group scored a mean of 8.2 (*SD* = 2.0). A one-way analysis of variance showed that this mean score did not differ significantly between groups. Thus, the entrance knowledge level of the groups did not differ.

On the basis of their level of prior knowledge subjects over all conditions were classified into three groups. For the classification the overall mean score of 8.3 and the standard deviation of 2.4 were used.

- Low knowledge: the group of subjects with a low level of prior knowledge ($< M - 1$ *SD*).
- Middle knowledge: the group of subjects with an average level of prior knowledge (within + 1 *SD* and - 1 *SD* around the mean).
- High knowledge: the group of subjects with a high level of prior knowledge ($> M + 1$ *SD*).

Table 5.2 shows the number of subjects with a low, middle, or high level of prior knowledge for each experimental condition.

Table 5.2

Numbers of subjects per level of prior knowledge for each group

	Level of prior knowledge			
Group	Low	Middle	High	Total
Controller	8	18	5	31
Concept	2	23	4	29
Control	2	20	6	28
Total	12	61	15	88

Posttest

At the end of the lab, all subjects were given a posttest that consisted of 18 multiple choice questions. Table 5.3 presents the mean scores of the posttest.

A one-way analysis of variance showed that there was an effect for the experimental condition ($F_{(2,85)} = 8.03, p < .001$). The group with the controller overview of hypotheses had the highest mean score (10.8), the Concept group had a mean score of 9.3, and the control group had the lowest mean score (8.5). On the level of prior knowledge, posttest scores also showed significant differences between groups (Kruskal-Wallis $KW_{(2,\ N = 88)} = 6.31, p < .05$). The subjects with a high level of prior knowledge had the highest mean score (10.9), the subjects with the middle level of prior knowledge scored a mean of 9.5, and the subjects with a low level of prior knowledge had the lowest mean (8.5). Figure 5.4 depicts the scores of the posttest. To gain an impression of the interaction between experimental condition and level of prior knowledge separate Kruskal-Wallis one-way analyses of variance were done for each experimental group. Results of these tests showed no differences and, therefore, interaction between experimental groups and level of prior knowledge is unlikely.

Table 5.3

Mean posttest scores of the groups for each of the three levels of prior knowledge for subjects

	Level of prior knowledge							
	Low (n = 12)		Middle (n = 61)		High (n = 15)		Total (n = 88)	
Group	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Controller (n = 31)	9.4	2.0	11.1	1.9	12.2	2.7	10.8	2.2
Concept (n = 29)	6.5	0.7	9.4	1.9	10.5	1.3	9.3	1.9
Control (n = 28)	7.0	4.2	8.1	2.7	10.2	2.5	8.5	2.8
Total	8.5	2.4	9.5	2.4	10.9	2.3	9.6	2.5

A comparison between the control group and both experimental groups combined gave a significant difference in favour of the groups with support (Mann-Whitney $U_{(1,\, N\,=\,88)} = 558.5$, $p < .05$). As was mentioned above, the control group had a mean score of 8.5 (SD = 2.8). The subjects that received support have a mean score of 10.1 (SD = 2.2) on the posttest.

Analysis of exploratory learning

For analyzing effects of prior knowledge on the posttest scores, subjects were grouped according to their individual prior knowledge scores. In this section the subjects' learning processes are used as dependent variable and as subjects worked in pairs with the fill-in forms individual prior knowledge scores had to be combined to create a prior knowledge score for each of the pairs. Combining the individual levels of prior knowledge in a pair resulted in five combinations: low-low, low-middle, middle-middle, middle-high, and high-high[11]. The five combinations were arranged into three groups of pairs:

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[11] Notable is that the combination low-high was not present.

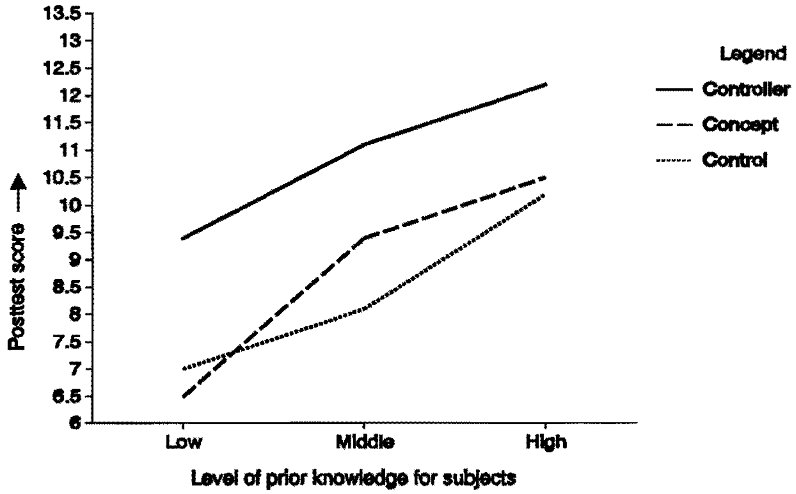

Figure 5.4 Mean posttest scores for the three experimental groups as a function of levels of prior knowledge.

- LOW PAIRS are pairs with low-low and low-middle combinations of individual scores;
- MIDDLE PAIRS are pairs where both subjects had a middle level of prior knowledge;
- HIGH PAIRS are pairs with middle-high and high-high combinations of individual scores.

This resulted in 9 low pairs, 13 middle pairs, and 7 high pairs over both experimental groups.

Global activity level

The first level of analysis assessed the global activity of the subjects in terms of the number of forms, the number of hypotheses, and the percentage of cells that were filled in. The percentage of cells was a relative score; for each pair of subjects the number of cells filled in was divided by the maximum number of cells they could have scored given the number of forms this pair had used.

Table 5.4 shows that overall the subjects used an average of 5 fill-in forms and that almost 87% of the cells on the forms were used. Furthermore, subjects explored an average of almost 5 hypotheses.

A t-test showed no significant differences between the Controller and Concept groups for each of the three general activity indicators. A Kruskal-Wallis one-way ANOVA showed no differences between the LOW, MIDDLE, and HIGH pairs for the indicators.

Table 5.4

Mean scores (M) and standard deviations (SD) of the general activity indicators for the experimental conditions

	Overview of hypotheses					
	Controller (n = 15)		Concept (n = 14)		Total (n = 29)	
Indicators	*M*	*SD*	*M*	*SD*	*M*	*SD*
Number of forms	5.1	1.3	4.9	1.2	5.0	1.2
Number of hypotheses	4.7	0.8	4.6	0.7	4.6	0.7
Percentage cells	86.7	9.9	86.1	8.2	86.4	9.0

Learning process validity

At the second level of analysis the statements given by the subjects were assessed on their learning process validity i.e., 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 aspects that should be present were determined e.g., in the cell EXPERIMENT subjects should note down the input variables, the output variables, and the values of the input variables. For five cells together, a total of 19 aspects was stated.

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 5.5 gives the learning process validity scores for the experimental conditions. Data in Table 5.5 show that overall the learning process validity score of the subjects was almost 37%. The highest score was in the cell EXPERIMENT where subjects scored 64.5% of the three aspects in this cell. In the cell PREDICTION a mean score of 11.7 % was achieved. Despite the heading, subjects did not predict the outcome of the experiment but usually predicted the validity of the hypothesis at hand. Furthermore, subjects sometimes noted down statements that could be scored in the cell VARIABLES & PARAMETERS or EXPERIMENT. The scores in the cells DATA INTERPRETATION and CONCLUSION were the result of positive scores on only a few of the aspects that could be scored. Aspects such as: noting down output and a remark about the validity of the hypothesis were frequently scored. However, aspects that required more profound analysis of output and generalization of findings were seldom or never found.

There are two significant differences between experimental groups on the learning process validity level. First, a difference was found for the cell EXPERIMENT (t (28) = 2.83, $p < .01$). Table 5.5 shows that the Controller group scored 75.1% of their maximum scores in the cell EXPERIMENT whereas the Concept group scored 53.1% of their maximum scores. Secondly, a difference was found for the cell DATA INTERPRETATION (t (28)= 2.12, $p < .05$). For the cell DATA INTERPRETATION, Table 5.5 shows that the Concept group scored a higher score (26.6%) than the Controller group (22.5%). No significant differences between groups were found on the basis of their level of prior knowledge. Separate Kruskal-Wallis one-way ANOVAs for the experimental groups showed no differences between prior knowledge groups for the total learning process validity score and, therefore, interaction between level of prior knowledge and overview structure is probably not present.

Table 5.5

Mean scores (M) and standard deviations (SD) of the learning process validity scores for the experimental conditions

	Overview of hypotheses					
	Controller (n = 15)		Concept (n = 14)		Total (n = 29)	
Cell	*M*	*SD*	*M*	*SD*	*M*	*SD*
VARIABLES & PARAMETERS	48.3	24.0	40.4	17.8	44.5	21.2
EXPERIMENT	75.1	21.3	53.1	20.7	64.5	23.5
PREDICTION	11.2	20.4	12.1	21.2	11.7	20.4
DATA INTERPRETATION	22.5	5.5	26.6	5.1	24.5	5.6
CONCLUSION	26.9	4.4	26.6	6.4	26.8	5.3
total[12]	38.9	9.3	34.4	6.8	36.7	8.4

Domain correctness

For domain correctness only those aspects of statements were assessed that were valid at the learning process validity level. If a subject made a mistake in one of the cells which caused mistakes in other cells, then the mistake was only scored once. 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, the score is 50% on domain correctness.

Results of the analysis at this level show that overall there is a high score on domain correctness with a mean of 89.7% (*SD* = 10.3). This means that almost 90% of the aspects that were scored learning process valid were also correct in domain-related sense. So, once the subjects made statements that were valid as an exploratory learning process, these statements were mostly correct at a

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[12] The total learning process validity is not an average of the scores of the five 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).

domain level. The trend that was observed at the previous level, in which some of the cells had lower scores than others, is not seen at the domain correctness level. The percentages are between 80% and 99%. For example, overall the subjects had a mean score of 80.6% (*SD* = 25.1) in the cell DATA INTERPRETATION, and 99.1% (*SD* = 4.6) in the cell EXPERIMENT.

There were no significant effects of the experimental conditions and the level of prior knowledge at this analysis level.

Consistency

At the fourth level of analysis the consistency of statements in different cells on a fill-in form was assessed. So, for example, a statement given by subjects in the cell PREDICTION was estimated on consistency with the statement given in the cell EXPERIMENT at the same fill-in form. In the analysis four specific relations were considered: EXPERIMENT-PREDICTION, EXPERIMENT-DATA INTERPRETATION, PREDICTION-DATA INTERPRETATION, AND DATA INTERPRETATION - CONCLUSION.

Analysis at this level was limited to cells containing statements that were both learning process valid (now estimating a more limited number of what was called 'crucial' aspects) and domain correct. As a result 25 relations were left for consistency assessment and of these relations only two were estimated as being inconsistent. Both these cases were concerned with the relation between EXPERIMENT and DATA INTERPRETATION.

A separate and more detailed analysis of the relation between the cell HYPOTHESIS and EXPERIMENT was made because differences between the two experimental groups appeared for the learning processes 'designing an experiment'. Indicators in analyzing this relation were:

- The number of appropriate experiments for the type of hypothesis at hand. There are seven types of experiments in total. If the hypothesis dealt with stability, a theoretical choice of six of these types of experiments was possible. If the hypothesis dealt with steady state error a theoretical choice of only three types of experiments was possible.
- The type of experiment that was used. This could be done with the simulation program or in an analytic manner.

Analyzing the experiments that subjects designed in the cell EXPERIMENT showed that the mean number of experiments overall was 9.6 (*SD* = 4.9). Subjects hardly made mistakes with the appropriateness of the experiment for the hypothesis at hand. Just one pair of subjects made one inappropriate choice. A t-test showed (t (28) = 2.22, $p < .05$) that the Concept group designed significantly more analytic experiments ($M = 2.3$, $SD = 1.7$) that could be done without the simulation program than the Controller group ($M = 1.1$, $SD = 1.1$).

Overall strategy

As a final analysis level the development of subjects' ideas through the set of fill-in forms was assessed. It was assumed that subjects' choices from the overview of hypotheses and the path through the hypotheses was an indication of their overall strategy.

Figure 5.5 shows the sequence of the hypotheses chosen for each overview condition[13]. As was explained in Subsection 5.2.1 the rules for choosing the hypotheses from the overview differed between groups. The Controller group had to choose one hypothesis per section and the Concept group two per section. In general, in both overview conditions subjects had chosen a variety of paths. No single path was favoured and followed by more than three pairs of subjects.

When the separate groups were considered it was found that in the Controller group thirteen pairs started with the first hypothesis (P-S) and two pairs started with the second hypothesis (P-SE). The domain expert was asked which path he would have taken in the controller overview and this was the path 1-3-5-7-8. Two pairs in the Controller group did choose this path. For the Concept group it was not necessary to explore the first hypothesis since other hypotheses in the first section could lead to sufficient insight in the concept of stability. However, ten pairs did explore it and only four pairs started with the second hypothesis. The domain expert would have chosen the path 2-3-4-6-8 which was not chosen by any of the pairs. There was one pair that came close with the path 2-3-4-6.

Table 5.6 gives the number of pairs that had chosen a certain hypothesis. The table lists the hypotheses in the order in which they were presented to the different experimental groups (see Figure 5.1).

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[13] S stands for stability, SE for steady state error and the action or combination of actions stand for the specific controller with those action(s) e.g., P stands for a P-controller.

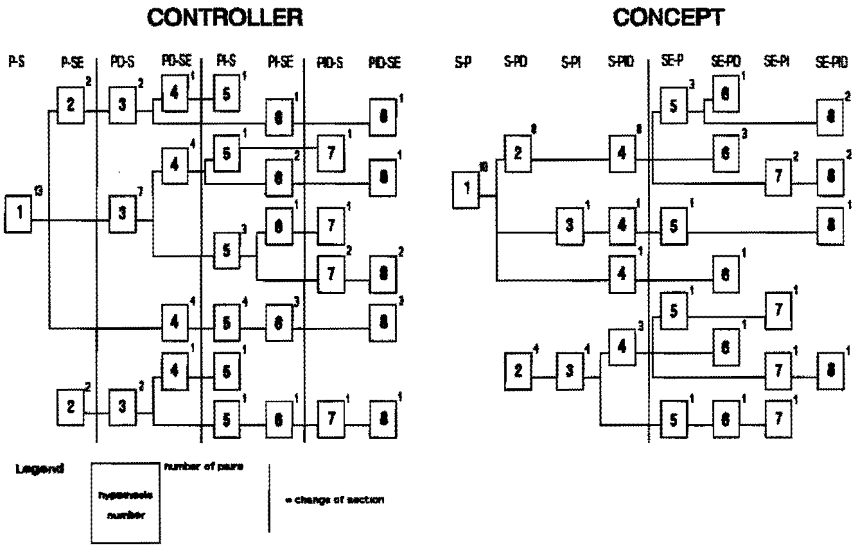

Figure 5.5 Paths through hypotheses set for both experimental groups.

A closer look showed that the frequency in which two of the hypotheses were used is not similar over both groups. These are the PI-S (S-PI) and the PID-S (S-PID) hypotheses. The hypothesis PI-S was chosen more frequently in the Controller group. The Concept group selected the hypothesis PID-S more frequently than the Controller group.

Table 5.6

Number of pairs that have chosen a specific hypothesis for each experimental group

Hypothesis	Controller (n = 15)	Hypothesis	Concept (n = 14)
P - S	13	S - P	10
P - SE	4	S - PD	12
PD - S	11	S - PI	5
PD - SE	10	S - PID	13
PI - S	11	SE - P	6
PI - SE	8	SE - PD	7
PID - S	5	SE - PI	5
PID - SE	8	SE - PID	6
Total	70	Total	64

5.2.3 Conclusions

The findings of Study 4 result in a number of conclusions on the influence of the experimental conditions and prior knowledge on both exploratory learning and learning outcome.

Instructional support measures

Extra support for structuring the exploratory learning process and the specific structure of the overview of hypotheses has an effect on performance. First, the expectation that students who received the off-line support performed better on a posttest than students who had to work with the simulation without the off-line support was confirmed.

Secondly, students who worked with the controller structure scored higher on the posttest than students working with the concept structure. This is, however, just the opposite of one of the expectations of the present study. It was expected that the concept structure would result in higher posttest scores because this structure stresses the fundamental aspects of the domain and supports the teacher's solution strategy to control problems. A possible explanation for the findings is that the controller structure could be more compatible with students needs and prior knowledge than the concept structure. In the textbooks, the controller structure is also employed and it is quite possible that students were more familiar with this point of view. Although teachers would prefer students to approach control problems with the concept structure, this structure does not recur in the textbooks. Likely, the concept approach is implicit (expert) knowledge and therefore not accessible, not even for students with high prior knowledge.

Prior knowledge

The level of prior knowledge is important for the posttest scores i.e., the higher the level of prior knowledge the higher the posttest scores. This effect was present for both experimental groups and the control group. However, no interaction was found between level of prior knowledge and the experimental condition. Students with a high level of prior knowledge were expected to gain a higher profit from the concept structure than the students with low prior knowledge, but data of the present study showed that both groups seemed to prefer the controller structure.

Quality of exploratory learning processes

Differences in quality of the exploratory learning processes matter; they can partly explain the results on posttest scores. One of the differences that was found is that students in the Controller group scored better in the cell EXPERIMENT on the learning process validity level than students in the Concept group. This means that the Controller group designed better experiments in the sense of more complete experiments. The Controller group more frequently stated the three required aspects of an experiment: their choice of input, the required output, and the value(s) of input variable(s) or parameter(s). It could be possible that this effect was strengthened by the fact that it is easier to design several experiments for one specific controller. This could have been an advantage for the Controller group since they had to explore the controllers one at a time. The Concept group, on the contrary, had to change between controllers all the time. This is in line with the findings on the consistency level that the Concept group designed more analytic experiments that could be done without the simulation than the Controller group. However, if the number of experiments designed in the cell EXPERIMENT are considered, there are no differences between the two groups. Thus, the difference that was found in the cell EXPERIMENT is probably not caused by the above mentioned advantage.

The effects found in the quality of the learning processes are in line with the results of the posttest scores. They were generally positive for the Controller group. However, differences in experimental conditions were reflected strongly in posttest scores but not profoundly in learning processes. Furthermore, the effect of the level of prior knowledge on the posttest scores was not found for the learning processes. The experimental groups both received the same type of support for exploratory learning processes (information sheets and fill-in forms). It might be possible that the analysis measures for the exploratory processes are not appropriate for measuring domain-specific differences.

The Controller and Concept group did not differ in activity level. Differences in post test scores, therefore, can not be explained from differences in general activity during the exploratory learning process.

Practice

Students do not perform exploratory processes too well, but practising the additional support may have been helpful. Although some aspects of the experimental set-up and the support measures are not exactly similar, results of the present study can partly be compared with results of Study 3[14]. In the previous study was concluded that the valid performance of the learning processes appeared to be the bottleneck in exploratory learning. Results of the present study show that performing exploratory learning processes remains difficult for students. Although in the current study students did not have to do the difficult process of hypothesis formation, they still did not do well on the other processes. In both studies interpreting data and drawing of conclusions was not done in depth and predicting the outcome of an experiment also caused difficulties.

A major finding in the present study is that experimental groups had higher learning outcomes. In the previous study the support measure showed no positive effect on learning outcome. Students in the previous study had to perform two new tasks in the same lab session that is, to learn to work with the support measures and to work out the assignment. An explanation could be found in related studies which show that additional support may draw away students' attention from the main task: working with the simulation (de Jong, de Hoog, & de Vries, 1992). One of the advantages of the present study was that students had practised to work with the support measures prior to the evaluative session and although this did not result in a high quality exploratory learning process, this may have helped them in giving more attention to the main task: the assignment. This underscores the general notion that experimen-

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[14] It is possible to compare the (two) experimental groups of the present study with the group that was offered fill-in forms with predefined hypotheses in the previous study.

tal instructions should be worked with over a longer period of time before students get used to new ways of learning and improvements are to be expected.

The conclusion with regard to the design of simulation-based learning environments is that offering structures of hypotheses is a potential fruitful support measure. Data of the present study showed that students choose various paths through the hypotheses and no path was strongly favoured. Structured overviews of hypotheses, therefore, left sufficient exploratory freedom for learners.

Secondly, the form of the structure influences learning outcome (although not in the expected direction). Studies on text structuring (e.g., Eylon & Reif, 1984) show that the type of structuring of information is reflected in students' knowledge bases and consequently influences problem solving behaviour. In a similar vein, it was assumed that the particular structure of a set of hypotheses directs students' moves in hypothesis space (Klahr & Dunbar, 1988) and, in this way, affects the resulting knowledge base. In summary, the conclusion is that offering structured overviews of predefined hypotheses as a means of support is a promising method. However, structuring and supporting movements in hypothesis space need to be studied in depth, before conclusive prescriptions for the design of simulation-based learning environments can be given.

CHAPTER 6

GENERAL CONCLUSIONS AND DISCUSSION

The main subject of this thesis is exploratory learning with computer simulations. Studies in this thesis resulted in an inventory of exploratory learning processes. Additionally, the inventory of exploratory learning processes was used as a basis for designing instructional support for exploratory learning and these support measures were evaluated. In the present chapter the initial research questions are addressed, results of the studies are integrated, and significant themes are further discussed.

6.1 Exploratory learning processes

The first research question of this thesis was: What are the learning processes that are implicated in exploratory learning? To answer this question two studies, Studies 1 and 2, were carried out with a simulation program in the field of control theory. Making use of thinking aloud protocols, students' learning was analyzed and findings were related to literature. This resulted in an inventory of exploratory learning processes. As a results of the Studies 1 and 2, the following processes were identified:

- model exploration;
- hypothesis generation;
- designing an experiment;
- predicting;
- interpreting output;
- evaluating;
- generalizing.

These processes are commonly found for scientific research but were until recently not associated with exploratory learning. Recent studies in which learners working with computer simulations were observed found similar exploratory processes (Friedler, Nachmias, & Linn, 1990; Klahr & Dunbar, 1988; Reimann, 1989; 1991; Shute & Glaser, 1990). The inventory of exploratory learning processes is well in line with Klahr and Dunbar's (1988) model that characterizes exploratory learning, analogous to problem solving (Simon & Lea, 1974), as a search in two spaces. Learners have to move between a space of hypotheses and a space of experiments. Learners test a hypothesis by designing experiments, and by interpreting output from experiments learners evaluate their current hypothesis.

An important issue is the reach of the inventory of exploratory learning processes. Can the exploratory learning processes in the inventory be generalized across domains? The domain of the studies in this thesis is control theory. A general characteristic of this domain is that it contains conceptual complex relations i.e., multivariate and dynamic relations. Only few studies in literature looked at exploratory learning in conceptually rich domains (e.g., Shute & Glaser, 1990). Mostly, simple task domains are used (e.g., Klahr & Dunbar, 1988). To study the reach of the inventory of exploratory learning processes, it should be tested for domains other than mechanical engineering. The inventory of exploratory learning processes was used in the domain of error analysis in chemistry by van Joolingen (1993). His study resulted in further analysis of the learning process 'hypothesis generation' into processes such as specialization or restriction of hypotheses.

Apart from the identification of the exploratory processes, the frequencies of the learning processes of students working with a simulation program were also determined. Results of Studies 1 and 2 showed that students made little use of some of the significant exploratory learning processes such as hypothesis generation. Even after students were encouraged to generate and test hypotheses by directive guidance, students did not make use of these processes.

6.2 Evaluation of instructional support

As learners were not inclined to use exploratory learning processes it was assumed that instructional support would help learners in exploratory learning. Therefore, the second research question of this thesis was: What is the result of instructional support, which is specifically designed to support exploratory learning processes, on learning outcome and the quantity and quality of the learning processes? Two experimental studies were performed, Studies 3 and 4, to evaluate the effect of specific types of instructional actions on exploratory learning. Research was done in the same educational context as the first two studies: students learning with a simulation program in the field of control theory.

Several instructional support measures were designed and evaluated in the Studies 3 and 4. First, providing information on the learning processes was examined in Study 3 by manipulating the type of information that subjects received about the learning processes. This information was domain-dependent or domain-independent. Results of Study 3 showed that the type of information that subjects received did not relate to quantity and quality of the learning processes and also had no effect on learning outcome. Second, instructional support measures for hypothesis generation were evaluated. Support for hypothesis generation was studied in Study 3 by giving pre-defined hypotheses to a part of the subjects. Results of Study 3 showed that subjects who were provided with hypotheses showed higher global activity and higher scores in domain correctness of their learning processes than subjects who did not receive hypotheses as instructional support measure. However, the effects on the quantity and quality of learning processes of the Hypothesis group did not directly result into higher learning outcome. In Study 4 hypothesis generation was supported in detail by manipulating the structure of an overview of hypotheses. The two overviews of hypotheses represented two approaches or movements in hypothesis space (Klahr & Dunbar, 1988). The controller structure represented a practical approach that arranged the hypotheses according to the types of controllers that could be used to regulate a mechanical system. The concept structure represented a theoretical approach that ordered the hypotheses according to fundamental concepts from the domain. Analysis of posttest scores showed that the Controller group scored higher on the posttest than the Concept group i.e., the Controller group had higher learning outcomes. Most important result of the analysis of learning processes was that the

Controller group designed better (more complete) experiments than the Concept group.

In sum, support for hypothesis generation resulted in positive effects on either learning outcome or quantity and quality of the learning processes. Other studies (van Joolingen, 1993; Shute & Glaser, 1990) also showed positive results and it may be concluded that supporting hypothesis generation can improve exploratory learning. However, when support for exploratory learning processes is supplied, attention should be given to a number of issues that are discussed in the next few sections.

6.3 Cognitive load

In Studies 3 and 4 a control group was provided with the same assignment and simulation program as the experimental groups. However, the control group did not receive instructional support such as fill-in forms, general information on the learning processes, and structured overviews of hypotheses. The effect on learning outcome[15] in Study 3 did certainly not show an advantage of the experimental groups over the control group. Moreover, the group with the highest level of support (domain-dependent information and hypotheses) had significant lower posttest scores than the control group. Other studies (de Jong, de Hoog, & de Vries, 1993; van Joolingen, 1993) showed similar negative effects of a high level of support. A possible explanation is that the instructional support measures had placed an additional cognitive load on subjects' working memory.

Sweller's (1988) cognitive load theory is based on the assumption that working memory has limited processing capacity. Especially novice learners in a domain direct their attention inappropriately and use weak problem-solving strategies, such as means-ends analysis, that require high processing capacity. Moreover, Chandler and Sweller (1991) suggested that instructional measures can direct cognitive resources toward significant features so that knowledge is acquired, but instructional measures can also be ineffective when learners are forced to engage in superfluous processing. Particularly, during hypothesis testing in exploratory learning the cognitive load should be reduced by using

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[15] Since subjects in control groups did not make use of fill-in forms, the control group could not be compared to experimental groups for the quantity and quality of the learning processes. The control group could only be compared to experimental groups for learning outcome.

conservative movements in hypothesis space (Klahr, Fay, & Dunbar, 1993) such as focusing on one dimension to be able to compare the outcomes of experiments appropriately.

In Study 3, learning to apply the exploratory processes might have interfered with acquisition of domain-dependent knowledge, as was apparent from the group with the highest level of support. Learners in the experimental groups had lower scores on the posttest, which measured domain-dependent learning outcome, than the control group. However, results also showed that the same group had high scores on quality of the learning processes. Furthermore, it might be possible that the instructional support measures have put an extreme cognitive load on learners working memory. Learners were not only quite new in the domain at hand, but were also unfamiliar with exploratory learning and the instructional support measures in the experimental setting. When learners can practice exploratory learning over a longer period of time the instructional measures could result in positive effects on learning processes as well as on learning outcome.

In Study 4 measures were taken that most likely reduced the cognitive load on learners' working memory. In contrast with the experimental procedure of Study 3, subjects in Study 4 were given the possibility to get used to the instructional support measures. In the lab session prior to the experimental session, subjects in the experimental groups were already provided with information and materials. Therefore, subjects in the experimental groups were familiar with elements of support and, accordingly, were more likely to concentrate on domain-related information. This might have contributed to the results of Study 4 that showed positive effects of the instructional support measures on learning outcome.

6.4 Domain-specific versus general knowledge

The contrast between domain-dependent and domain-independent knowledge and the influence of knowledge types on learning has been the reason for a considerable body of research. In a recent study, Schauble, Glaser, Raghavan, and Reiner (1992) found that exploratory learning was the result of both domain-independent strategies and heuristics and learner's individual domain-dependent knowledge. Subjects in their study were given a hypothesis-testing task in a computer lab about an unfamiliar subject. Although subjects were novices, they used general strategic knowledge as well as individual domain-specific knowledge about e.g., task demands, and cause and effect.

The Studies 1 and 2 of this thesis also showed that learners asked for help on basic domain-specific knowledge such as definitions of concepts. But when learners in Study 3 were supported with domain-dependent information on exploratory learning processes, together with general information on these processes, results showed that it did not improve exploratory learning or learning outcome. However, when domain-dependent prior knowledge of learners was assessed in Study 4 it showed to have significant effects on learning outcome. So, when learners are supported with domain-dependent information, one should consider basic domain knowledge or domain-dependent information related to learning processes. A prerequisite that is mentioned for metacognitive instruction (Veenman, 1993) is the integration of general instruction about learning with domain-dependent instruction. In general, it should be emphasized that both domain-dependent and domain-independent (prior) knowledge require attention in research and education on exploratory learning.

Another question related to prior knowledge is: Does the type of prior knowledge affect the effects of instructional support measures on learning processes and learning outcome? This issue is further discussed in the next section. The contrast between general and domain-specific learning processes also influences the assessment of learning processes. The question whether learning processes should be assessed by general or domain-specific criteria is addressed in Section 6.7.

6.5 Learner attributes

Research on Aptitude Treatment Interaction (ATI) (Cronbach & Snow, 1977) assumed that learner attributes affect the effects of instructional measures on learning outcomes. In Goodyear, Njoo, Hijne, and van Berkum (1991) an overview is given of learner attributes that might influence learning with computer simulations. Examples are cognitive styles like Field Dependency and Field Independency, and learning approaches like deep or surface processing.

Most of the learner attributes that were discussed in Goodyear et al. (1991) have a rather static character and extend to attributes that can be almost considered as personality traits. Are exploratory learning processes, which represent competence in scientific reasoning, such a stable attribute or are they dependent on the domain or task at hand? Glaser et al. (1992) studied exploratory learning across different domains. Results of this study showed that subjects adapted their learning processes to the constraints of the task and domain at hand. Van Joolingen (1993) constrained subjects by the design of the learning environment in such a way that they were stimulated to explore in a theorist's or experimenter's way (Klahr & Dunbar, 1988). Results of van Joolingen's (1993) study showed that, regardless of any personal preferences, subjects were influenced by the design of the learning environment. Both of these studies suggest that exploratory learning strategy or processes are not a static trait but can be influenced by the domain or task at hand or by specific instructional support measures.

Furthermore, Schauble, Klopfer and Raghavan (1991) suggest that competence in exploratory learning develops by experience over a longer period of time. They studied children in two experimentation environments. Over six sessions, children's competence in exploratory learning increased, as measured by percentages of valid inferences. The validity of these inferences were determined by two criteria. First, inferences had to be correct and, second, inferences had to be based on sufficient and unambiguous data from the investigations. Improvement of children's competence in exploratory learning was influenced by the type of task: an engineering or a scientific task. The main objective of the engineering task was to make a desired outcome occur, whereas the scientific task aimed at identification of causal relations between variables. Children who started with the engineering task made the most improvements overall.

In this thesis one of the learner attributes is studied in relation to instructional support measures and learning outcome. This attribute, prior knowledge, is also frequently mentioned in other studies (Glaser et al., 1992; Schauble et al., 1991) as a factor that contributes to the successful use of computer simulations. In Study 4 prior domain-dependent knowledge of subjects was assessed and its relation with learning outcome and the quantity and quality of the learning processes was studied. Results of Study 4 showed that prior knowledge was related with learning outcome i.e., the higher the level of prior knowledge the higher the learning outcome. Prior domain-dependent knowledge, however, was not related with quantity and quality of learning processes. Furthermore, contrary to what was expected, no interaction effects were found between support measures and the level of prior knowledge.

Prior knowledge in Study 4 was limited to domain-dependent knowledge. The effects of domain-independent knowledge on learning outcome and the interaction with instructional support measures was studied by e.g., Shute (1990). She measured domain-independent knowledge by a test battery on general knowledge and found that learners with low scores on prior domain-independent knowledge performed poorly regardless of the level of structure of the learning environment. Learners with high scores on prior domain-independent knowledge performed better in a structured learning environment. Therefore, it might be assumed that not only domain-dependent knowledge but also domain-independent knowledge affects the effects of instructional measures on learning outcome. Further research should study the interdependencies between domain-dependent as well as domain-independent prior knowledge, instructional support measures, learning outcome and the quantity and quality of learning processes.

6.6 Learning processes versus learning outcome

What can be learned from the results of the studies in this thesis about the interdependencies between instructional support, learning processes, and learning outcome? If instructional support measures improve the quality and quantity of the learning processes as well as domain-dependent learning outcome, it might be assumed that learning processes act as a intervening variable between instructional support measures and learning outcome. In other words, instructional support measures affect exploratory learning processes that on their turn affect learning outcome.

Results of Study 3 showed that there were significant effects from the instructional support measures on learning processes but in Study 4 these effects hardly occurred. Effects of the instructional support measures on learning outcome, however, showed just the contrary. In Study 3 the control group even had higher scores than one of the experimental groups but in Study 4 one of the experimental groups had significantly higher scores than the control group. So, in Study 3, when the support measures had an effect on learning processes it did not affect learning outcome. In Study 4, when the support measures had an effect on learning outcome, the effects on learning processes were most likely not sufficient to account for the effect on learning outcome.

Results of the Studies 3 and 4 did not verify that improvements in learning processes, caused by instructional support measures, determined higher learning outcomes. Despite these results of the Studies 3 and 4, I do not reject the hypothesis of exploratory learning processes as an intervening variable. Other studies (Shute, Glaser, & Raghavan, 1989; Veenman, 1993) confirmed that instructional support measures improved learning processes as well as learning outcome. Results of Studies 3 and 4 can be caused by other factors already explained in earlier sections of the present chapter. A possible explanation of the results of Study 3 was that learners' cognitive load was too high because learners had to learn domain-dependent knowledge as well as learn to explore a domain. A possible explanation of the results of Study 4 is discussed in the next section. The analysis measures that were used to determine the quality of the learning processes were likely not sufficient for measuring detailed domain-dependent differences.

6.7 Research on learning processes

Research on learning processes requires a specific method such as thinking-aloud protocols. In the Studies 1 and 2 this method was used to assess learners' exploratory learning processes. The verbal protocols offered a high level of detail and resulted into insight in exploratory learning processes. For the evaluation of the instructional support measures in the Studies 3 and 4 such a high level of detail was not required because the exploratory learning processes were already identified. Based on the criteria for assessing the learning processes in the Studies 1 and 2, key features of the exploratory learning processes were determined. These key features fulfilled two goals. First, the key features were offered to learners as support on the information sheet. Second, statements that were noted down on the fill-in forms by learners themselves were used as a reflection of the exploratory learning processes and criteria to assess these statements were also determined by these key features. This new method had a major advantage. Analysis of the statements on the fill-in forms was more efficient than protocol analysis and, therefore, a relatively high number of subjects could participate in the studies. The fact that certain aspects of exploratory learning could not be evaluated, such as the sequence of the learning processes, was not considered a disadvantage because the statements on the fill-in forms provided sufficient data for analysis of the exploratory learning processes.

The learning processes were not only assessed by the key features but also on different levels such as global activity, domain correctness, and consistency. The analysis levels were developed to measure diverse qualities of the learning processes. Shute, Glaser, and Raghavan (1989) determined thirty exploratory behaviours of learners working with Smithtown, a simulation-based learning environment on micro-economics. The exploratory behaviours were ordered into eight learning indicators such as: activity level, efficient tool usage, and effective generalization. These eight learning indicators were further categorized into three categories:

- thinking and planning indicators;
- data management discriminating indicators;
- activity/exploration discriminating indicator.

The learning indicators and the analysis levels in this thesis both measure general features of the exploratory learning processes. Other studies make use of domain-dependent criteria for the assessment of exploratory learning. Examples are: variables that were used in the hypotheses by subjects (Klahr & Dunbar, 1988) or the precision level of the relations in the hypotheses that were stated by subjects (van Joolingen, 1993). The analysis levels that measured general features of learning processes were appropriate for Study 3. However, in Study 4 the instructional support measures were highly domain-dependent. These support measures showed effects on learning outcome but did not result in effects on the quality and quantity of the learning processes. The conflicting results might have been caused by the character of the assessment criteria. As the support measures were domain-dependent, the criteria for assessing the learning processes should also have been domain-dependent. It is possible that the support measures in Study 4 required more domain-dependent measurements. Future research should develop the levels of analysis in further detail and for general as well as domain-specific purposes.

6.8 Implications for education and instructional design

The studies in this thesis were conducted within a regular curriculum. Performing experiments in regular curricula means that possibilities for implementing experimental conditions are limited. However, the great advantage is that research is done in situations for which the conclusions are highly relevant. For the Department of Mechanical Engineering the studies already resulted into several adjustments to the organization of the computer lab. The findings of this thesis can be generalized to education and instructional design in general.

Exploratory learning with computer simulations is an approach that is well in line with the cognitive viewpoint on learning. However, when computer simulations are used as exploratory environments it is necessary to support learners with specific instructional measures for the exploratory learning processes. First, studies in the present thesis contributed to an inventory of learning processes that can be used for describing potential problems of students who are learning with a computer simulation. The inventory also serves as a basis for designing instructional support measures that are specifically appropriate for exploratory learning. Second, in this thesis it is argued that traditional instructional support measures are not sufficient to support learners in exploratory environments and that exploratory learning requires innovative instructional support measures. However, for successful use of simulation learning environments, learners should be allowed sufficient time to get familiar with the new instructional measures and materials.

In the studies in this thesis, learners were supported with materials that structured their exploratory learning processes and especially hypothesis generation was supported with several instructional measures. Results of Study 3 showed that providing learners with predefined hypotheses had positive effects on some of the analysis levels and exploratory learning processes. The instructional action in Study 4 consisted of two types of structured overviews of hypotheses, representing different movements in hypothesis space (Klahr & Dunbar, 1988). Results of Study 4 showed that supporting the process of hypothesis generation is dependent on domain specific variables, as was apparent in the structure of the hypothesis space, and learner attributes such as prior knowledge. Subjects in Study 4 preferred the practical structure of hypotheses, regardless of their level of prior knowledge. But learners with a high level of prior knowledge had higher learning outcomes than learners with a low level of prior knowledge.

Additionally, instruction for exploratory learning should likely, at first, be adjusted to learners' mental model. Results of Study 4 showed that the practical approach was more compatible with learners' point of view than a theoretical approach. Schauble, Klopfer, and Raghavan (1991) found similar results in their study of learners in two experimentation environments. The experimentation environments were designed to encourage an engineering and a scientific approach. In the engineering environment learners attempted to make a desired outcome occur and in the scientific environment learners had to identify causal relations between variables. Schauble, Klopfer, and Raghavan (1991) recommended to build upon familiar ways of thinking when learners have to master new strategies. Learners were more accustomed to the engineering environment and results showed that learners who started with the engineering task and later moved on to the scientific task showed better results than learners who performed the tasks in reverse order.

Another practical implication of the studies in this thesis is the possibility to assess both learning processes and learning outcome. Jonassen (1991b) argued that constructivism also needs contructivistic methods of evaluation. As learning processes take a prominent role in constructivism, assessment of the mental processes of learners is required. The fill-in forms from the Studies 3 and 4 of this thesis can be used as an instrument for assessing learning processes and the criteria for assessment of learning processes can be based on the analysis levels.

Obviously, one of the important contributions of educational research is the application of results to education and instructional design. Findings in this thesis contribute to insight in exploratory learning that can be applied in the design of simulation learning environments. However, these findings cannot be considered as general prescriptions. Most studies in literature (e.g., Gery, 1987; Rowe, 1984; Steinberg, 1984) present prescriptions for successful design and implementation of instructional simulations. Actually, designers of simulation learning environments (such as professional courseware designers, teachers, and domain experts) should not only be supported with general prescriptions but should also be provided with the situations in which they can apply certain prescriptions. Successful use of simulation learning environments cannot be achieved by a single set of prescriptions but should be supported by a set of 'conditional' rules (Njoo, de Jong, Byard, & Tait, 1991). These rules present educationally appropriate decisions e.g., choice of instructional strategies or user interface design aspects, for promoting effective learning from simulations in certain educational situations. These educational situations can be characterized by domain characteristics, learner attributes, or by combinations of both. When sufficient empirical studies are available, the rules can be presented as a database of educational rules for promoting effective learning with simulation learning environments. At present, empirical research in the field of exploratory learning with computer simulations has not resulted in such a database. Future empirical research will contribute to such a database and will hopefully result in successful design and implementation of simulation learning environments.

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APPENDIX A

The following criteria were used at the learning process validity level for assessing statements of students in the different cells:

VARIABLES&PARAMETERS
- Variables/parameters*[1]
- Differentiation between variables and parameters
- Differentiation between independent and dependent variables
- Relations between variables and/or parameters
- System

HYPOTHESIS
- Relation between two or more variables and/or parameters*

  At the level of system theory, this has to be a statement about the properties of a class of systems.
  At the level of a specific system, this has to be a statement about the behaviour of the system in time and for any input signal.

EXPERIMENT
- Input variables/parameters*
- Output variables/parameters*
- (Range of) values of input variables/parameters

PREDICTION
- Results of the experiment (qualitative/quantitative)*

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[1] * = Aspects that absolutely had to be present for analysis of the consistency level (see the Sections 4.3.2 and 5.2.2).

At the level of system theory, this is a statement about the output, given a system (specified in the experiment).
At the level of a specific system, this is a statement about the output, given a certain input signal.

DATA INTERPRETATION

- Output (graphs/data)*
- Discussion of characteristics of the output*
- Discussion of the properties of the (class of) system(s)*
- Comparison with the prediction
- Comparison with other graphs/data
- Discussion about the experiment as a test for the hypothesis

CONCLUSION

- Validity of the hypothesis*
- Discussion of the model*
- Generalization to other models
- Generalization to control theory

APPENDIX B

In the following example the scoring of learning process validity is illustrated by discussing data analysis 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[2].

The students did not use the cell VARIABLES & PARAMETERS. In the cell HYPOTHESIS they 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 the 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;
- the values to give to the variables to be manipulated.

---

[2] Quotations from the protocols are translated from Dutch.

As a consequence they received only one out of three possible credit points for the cell EXPERIMENT.

In the cell PREDICTION the students correctly stated a prediction, indicating the expected results of an experiment. Figure 1 shows that they did this in a graphical way.

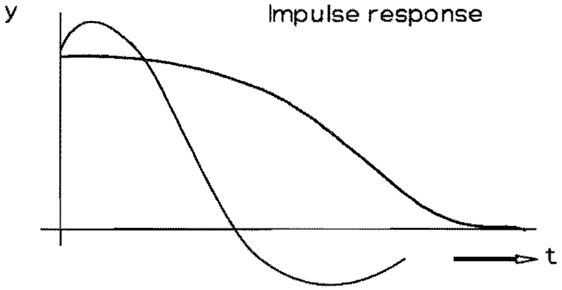

Figure 1. Example of students' notes in the cell PREDICTION.

For the cell DATA INTERPRETATION six criteria were used in the assessment. As is shown below the students indicated on their form only one of these: they noted down the (graphical) output of the simulation run (see Figure 2). 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.

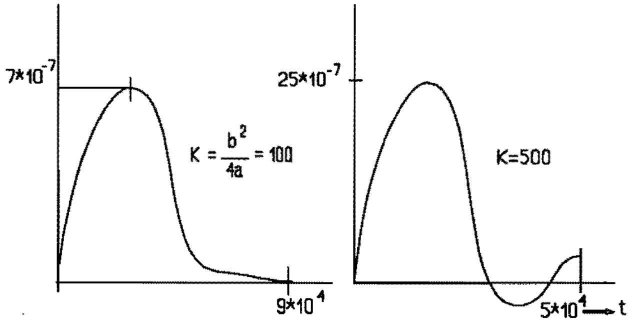

Figure 2. Example of students' notes in the cell DATA INTERPRETATION.

They did not:

- discuss the characteristics of the output;
- make a comparison to the prediction;
- infer important characteristics of the system;
- relate output to the experiment;
- make a comparison to other experiments, graphs, or data.

The statements in the cell CONCLUSION are shown in Figure 3.

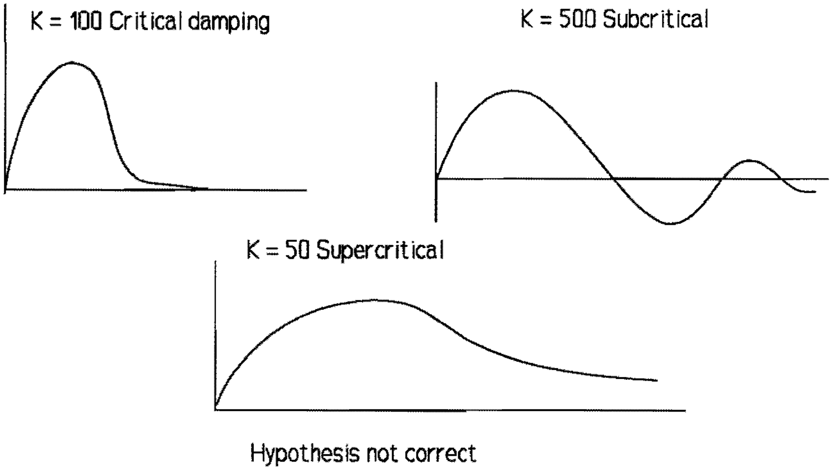

Figure 3. Example of students' notes in the cell CONCLUSION.

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.

NOTE

Parts of this thesis are based on articles that have been published earlier. At various points the original text in the articles was modified for publication in this thesis.

Chapter 1:

Goodyear, P., Njoo, M., Hijne, H., & Berkum van, J.J.A. (1991). Learning processes, learner attributes and simulations. *Education & Computing, 6,* 263-304.

Chapter 3:

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

Chapters 3 and 4:

Njoo, M., & Jong, T. de (1993). Exploratory learning with a computer simulation for control theory: learning processes and instructional support. *Journal of Research in Science Teaching, 30,* 821-844.

Chapter 5:

Njoo, M. & Jong, T. de (1993). Supporting exploratory learning by offering structured overviews of hypotheses. In D. Towne, T. de Jong, & H. Spada (Eds.), *Simulation-based experiental learning* (NATO ASI series) (pp. 207-225). Berlin: Springer.

ACKNOWLEDGEMENTS

In the writing of this thesis I have been supported by a number of people. In particular, I would like to acknowledge my gratitude to:

Ton de Jong for his inspiring support. I have appreciated the open atmosphere and his innovating view on learning and instruction with computer simulations. Prof. dr. J.M. Pieters and prof. dr. D.G. Bouwhuis for taking over the supervision from the late prof. dr. D.W. Vaags and for their thoughtful comments on the manuscript of this thesis.

Wouter van Joolingen and Erica de Vries for our many discussions and for their critical review of the manuscript. I could always count on them for advice and assistance. All of my former colleagues at Eindhoven University, especially Peter Verkerk and Monica Ferguson-Hessler, for exchanging ideas. Also, colleagues of the DELTA project SIMULATE[3] for a motivating period.

Furthermore, I would like to acknowledge special thanks to Jos Banens of the Department of Mechanical Engineering. He made it possible to perform the studies within the regular curriculum and shared his expert view on the domain. I have received valuable assistance from Stephan van den Akker and Christian Rademaker. They assisted in the studies and spent many hours on laborious analysis of data. Also, special thanks for the cooperation of Bram de Jager and Leo Braak and thanks to the students who participated in the experiments.

Finally, I would like to thank my colleagues, friends and family for their indispensable enthusiasm and encouragements.

Melanie Njoo
Diemen, January 1994

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[3] The studies in this thesis were performed in the context of SIMULATE. SIMULATE was part of DELTA project SAFE (D1014) and was partially funded by the European Community.

SAMENVATTING

(summary in Dutch)

Het onderwerp van het proefschrift is exploratief leren met behulp van een computersimulatie. Tijdens exploratief leren verwerft een student op actieve wijze kennis in een open leeromgeving zoals bijvoorbeeld multimedia-systemen of computersimulaties. Een computersimulatie is een computerprogramma dat een model van een proces, principe of systeem geeft. Een student kan variabelen en parameters van het model manipuleren en het programma toont de resultaten van de manipulaties. In vergelijking met andere leeromgevingen levert het leren met computersimulaties belangrijke voordelen op. Wanneer studenten met computersimulaties leren dan kunnen ze door middel van exploratie de kennis zelf ontdekken en verwerven. Deze vorm van leren sluit goed aan bij de huidige leertheorieën die zijn gebaseerd op inzichten uit de cognitieve psychologie en zijn beïnvloed door het constructivisme. Deze theorieën beschouwen leren als een actief proces waarbij een student de aangeboden informatie niet simpelweg kan opnemen maar zelf zal moeten construeren en structureren.

Het onderzoek in dit proefschrift richt zich op twee aspecten. Ten eerste is het onderzoek gericht op de exploratieve leerprocessen van studenten die leren met behulp van een computersimulatie. Het tweede aspect is de instructie die kan worden gegeven om exploratief leren te optimaliseren. Begrip van exploratief leren is van belang voor het ontwerpen van open leeromgevingen.

In Hoofdstuk 1 wordt een begin gemaakt om vanuit de bestaande literatuur tot een invulling van het begrip exploratief leren te komen. De drie onderzoeksgebieden die hierbij als basis dienen zijn: probleemoplossen, zelfontdekkend leren en inductief leren. Uit de beschreven onderzoeken blijkt dat deze visies veel overeenkomsten vertonen die betrekking hebben op het constructieve karakter van leren. Tevens wordt in Hoofdstuk 1 een algemene inleiding gegeven over computersimulaties als open leeromgevingen.

De studies uit dit proefschrift zijn uitgevoerd aan de Faculteit Werktuigbouwkunde van de Technische Universiteit Eindhoven. Het betreft het practicum 'Werktuigkundig regelen' van de vakgroep Theoretische Werktuigkunde. In dit practicum wordt gewerkt met het simulatieprogramma PCMatlab (© Mathworks). De context waarin de studies zijn uitgevoerd en achtergronden over het practicum en het simulatieprogramma zijn beschreven in Hoofdstuk 2.

Vervolgens wordt in Hoofdstuk 3 de literatuur aangevuld met onderzoeken die specifiek betrekking hebben op leren met computersimulaties. De onderzoeken die bij aanvang van dit proefschrift beschikbaar waren leverden onvoldoende inzicht in de specifieke exploratieve leerprocessen die plaatsvinden als studenten leren met computersimulaties.

Om inzicht te verkrijgen in de exploratieve leerprocessen van studenten zijn twee empirische studies verricht. In de Studies 1 en 2 (Hoofdstuk 3) zijn met behulp van hardop-denk protocollen de leerprocessen van studenten geïnventariseerd en geanalyseerd. Resultaten van deze twee studies zijn gecombineerd met recente bevindingen uit de literatuur in een overzicht van exploratieve leerprocessen. De leerprocessen zijn:

- modelexploratie;
- hypothesevorming;
- ontwerpen van experimenten;
- voorspellen;
- interpreteren van de uitvoer;
- evalueren;
- generaliseren.

Bij modelexploratie onderscheidt de student de variabelen en parameters van het model om vervolgens bij hypothesevorming ideeën te genereren over verwachte relaties in het model. De simulatie geeft de student de mogelijkheid deze ideeën te testen met behulp van experimenten. Door het voorspellen van de uitkomsten van de experimenten en het interpreteren van de uitvoer bouwt de student inzicht in het model op. Vervolgens kan de student de verkregen inzichten evalueren en generaliseren. Indien nodig kan de student de ideeën over de relaties in het model bijstellen. De in dit proefschrift onderscheiden exploratieve leerprocessen sluiten goed aan bij recente onderzoeken die exploratief leren voorstellen als het afwisselend zoeken in een hypotheseruimte en een experimentruimte.

De beschreven leerprocessen stellen hoge eisen aan de studenten. Uit de Studies 1 en 2 en onderzoeken uit de literatuur blijkt dat studenten problemen ondervinden bij de uitvoering van de exploratieve leerprocessen. Het ondersteunen van deze leerprocessen met behulp van specifieke instructie en materialen die zijn ontwikkeld op basis van de inzichten over de exploratieve leerprocessen kan studenten wellicht helpen bij het exploratief leren.

In Hoofdstuk 4 wordt een experimentele studie gerapporteerd waarin ondersteuning voor de exploratieve leerprocessen wordt geëvalueerd. In deze studie, Studie 3, worden studenten bij het uitvoeren van de leerprocessen ondersteund met:

- informatie over de leerprocessen;
- werkformulieren waarop de studenten de leerprocessen kunnen structureren.

Afhankelijk van de experimentele groep waartoe de studenten behoren krijgen zij alleen algemene informatie over de leerprocessen, danwel deze informatie aangevuld met vakinhoudelijke informatie. Ten tweede krijgen studenten, afhankelijk van de experimentele groep waartoe zij behoren, werkformulieren met of zonder hypothesen om te testen. De notities van de studenten op de werkformulieren worden geanalyseerd op vijf niveaus die elk een verschillend aspect van de exploratieve leerprocessen vertegenwoordigen. De vijf analyseniveaus zijn: globale activiteit, leerprocesvaliditeit (de uitvoering van de leerprocessen), domeincorrectheid, consistentie en totale exploratiestrategie. Studie 3 wijst uit dat het ondersteunen van studenten door het verstrekken van hypothesen positieve effecten heeft op de globale activiteit en de domeincorrectheid van de leerprocessen.

In Studie 4 (Hoofdstuk 5) worden studenten met soortgelijke materialen als in Studie 3 ondersteund. In deze experimentele studie worden studenten specifiek ondersteund in het leerproces 'hypothesevorming' met een overzicht van hypothesen. Studenten kunnen uit het overzicht een aantal hypothesen kiezen die ze gaan onderzoeken en bepalen hiermee hun exploratiestrategie. De structuur van het overzicht van hypothesen wordt gevarieerd voor de twee experimentele groepen: een practische ordening van hypothesen en een conceptuele ordening van hypothesen. Verder wordt in Studie 4 bij de analyse van de bevindingen rekening gehouden met het voorkennisniveau van de studenten wat betreft de vakinhoud. Resultaten tonen dat de studenten die met de practische structuur werken beter scoren op de eindtoets. Ook blijkt dat het voorkennisniveau effect heeft op het leerresultaat. Dit betekent: hoe hoger het voorkennisniveau, hoe hoger de score op de eindtoets. Dit effect is niet afhankelijk van de structuur van het overzicht van hypothesen waarmee wordt gewerkt.

In Hoofdstuk 6 worden de bevindingen van de vier studies uit dit proefschrift besproken. Ook worden de implicaties behandeld van de bevindingen voor het ontwerpen van simulatie-leeromgevingen en de inrichting van het onderwijs rondom deze leeromgevingen. Resultaten van het onderzoek die hiervoor kunnen worden gebruikt zijn ten eerste een inventarisatie van de exploratieve leerprocessen. Deze inventarisatie is bruikbaar voor de identificatie van problemen van studenten in termen van de exploratieve leerprocessen. Ten tweede, heeft het onderzoek verschillende vormen van instructie geëvalueerd die specifiek zijn ontwikkeld voor exploratief leren. Uit de evaluatie van de verschillende vormen van ondersteuning blijkt dat een deel van de materialen een positief effect heeft op de uitvoering van de exploratieve leerprocessen en het leerresultaat. Met name het ondersteunen van het leerproces 'hypothese-vorming' verdient aandacht in simulatie-leeromgevingen. Hierbij moet echter rekening worden gehouden met de structuur waarin de hypothesen worden aangeboden en in hoeverre deze structuur aansluit bij het mentale model van de studenten. In het algemeen geldt dat instructie bij een open leeromgeving een ondersteunend en niet sturend karakter moet hebben. De ondersteuning moet de leerprocessen van de student bijsturen, zodat ernstige problemen kunnen worden voorkomen, maar moet tevens rekening houden met de exploratieve vrijheid van de student.

CURRICULUM VITAE

Melanie Njoo was born on July, 4, 1962 in Bandung (Indonesia). In 1980 she finished her pre-university education at the 'Christelijke Scholengemeenschap Rijswijk' and started her studies in Psychology at Leiden University (the Netherlands). In 1988 she graduated in Educational Psychology and joined the Department of Philosophy and Social Sciences at Eindhoven University of Technology. For Eindhoven she participated in the European DELTA project Simulation Authoring Tools Environment (SIMULATE). The SIMULATE project resulted in the requirements and specifications for an authoring environment that can be used for designing intelligent simulation learning environments. Since 1992 she works for BSO/Instruction Technology BV, which is a subsidiary of BSO/ORIGIN. BSO/Instruction Technology supports organizations with the implementation of new information technology by providing services such as consultancy, communication, training, and workplace design.

STELLINGEN

behorend bij het proefschrift

Exploratory learning with a computer simulation:
learning processes and instructional support

1. De grote praktische voordelen die simulatie-leeromgevingen bieden boven het leren in praktijksituaties hebben tot gevolg dat de onderwijskundige voordelen niet volledig worden onderkend.

   Hoofdstuk 1, dit proefschrift

2. Richtlijnen voor het ontwerpen van simulatie-leeromgevingen moeten tevens de condities beschrijven waaronder deze richtlijnen gelden.

   Hoofdstuk 6, dit proefschrift

3. Er zijn nog onvoldoende evaluatiemiddelen om de leerprestaties van studenten vast te stellen in termen van leerprocessen.

4. Bij de ontwikkeling en implementatie van geautomatiseerde informatiesystemen is specifieke aandacht voor de werkprocessen van de gebruikers onontbeerlijk.

5. De voorgenomen wetgeving voor de meldingsplicht van fraude door accountants vergroot wederom het aantal onbezoldigde rijksambtenaren.

6. Zolang promovendae het nodig achten om een stelling te wijden aan de positie van de vrouw in de samenleving, kan deze positie nog worden verbeterd.

7. Een literair ballet gaat voorbij aan het ware medium dans.

8. Aangezien de overgangen tussen posities, beweging tot dans maakt, kunnen dansnotaties zoals Laban en Benesh beter bewegingsnotaties worden genoemd.

9. Een groot gedeelte van het aanbod op de Nederlandse televisie getuigt van een goed besef van de theorie van 'cognitive load'.

Sweller, J. (1988). Cognitive load during problem solving: effects on learning. Cognitive Science, 12, 257-285.

10. Het terugdringen van de overheidsbijdrage in de gezondheidszorg in Nederland zal uiteindelijk leiden tot de situatie 'No pay, no cure'.

Melanie Njoo
Diemen, 10 maart 1994