Learning and Instruction with Computer Simulations: Learning Processes Involved*

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Abstract: Nowadays prevalent learning theories state that in the study process the learner is actively involved in constructing and reconstructing his/her knowledge base. This conclusion is reflected in modern approaches to teaching that have abandoned viewing the learner as an 'empty box' into which knowledge could be poured, and stress the active role of the learner and the importance of his/her foreknowledge. Some forms of Computer Assisted Instruction are well suited for this teaching approach. The use of hypertext-like systems, in which learners are encouraged to explore a domain, is such an example. A second example of CAI that elicits exploratory behaviour is simulation-based learning.

It is, however, also evident that exploratory learning puts a high cognitive demand on the learner. Instructional support is needed if learning from simulations is to be effective. In practice this support is often provided by human tutors. The topic of the SIMULATE project is to investigate how this support can be given by a computer learning environment. We have termed

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environments that combine a simulation with (intelligent) support: Intelligent Simulation Learning Environments (ISLEs).

In our analysis we identified four characteristics of instructional use of simulations: presence of (simulation) models, presence of instructional goals, elicitation of exploratory learning processes and possibility of learner activity. The significance of these characteristics for designing an Intelligent Simulation Learning Environment is assessed by combining these characteristics with the four 'classical' design components of Intelligent Tutoring Systems: the domain, learner, instruction, and learner interface component. Combining components and characteristics leads to a descriptive framework in which ingredients necessary for ISLEs can be placed. The present chapter summarises these findings and puts an emphasis on 'exploratory learning processes'.

Keywords: Exploratory learning, computer simulations, learning processes

Introduction

There is a clear tendency in contemporary instructional design to create learning environments in which learners are not offered 'ready made', directly consumable knowledge, but in which they have to create their own knowledge. Self [33] has labelled these environments 'cognitive gymnasia'. One example of such a type of learning environment can be found in *computer simulations.*

Computer simulations are indeed a popular type of computer assisted instruction. A recent survey [3] shows that about 50% of the 300 CAI programs listed in a database of CAI used in Higher Education in the Netherlands is indicated as being a simulation or a combination of a simulation and another type of CAI (e.g., drill or tutorial).

The reasons that simulations are so popular may vary with the goals for which they are used. First, simulations used for teaching *skills* or *procedures* offer very practical advantages, such as being able to introduce catastrophes (e.g., in nuclear power plants), the reduction of stress (e.g., in treating patients in medical simulations) and cost effectiveness (e.g., flight simulators or laboratory experiments).

Second, when the simulation is about *dynamic models*, it allows natural *time scale* to be altered, so that processes may be speeded up or slowed down in order to make them more visible to the learner.

Third, simulations may be used to *simplify models* from the real world in order to have them match the prior knowledge and level of cognitive development of the learner.

These reasons for using simulations are all subordinate to the fact that simulations offer the opportunity for *exploratory* (or *scientific discovery*) learning, a way of learning regarded as having advantages by many authors [amongst others 1, 23, 24, 34] though some studies [31, 36, 38] don't find discovery learning more effective, merely more efficient than non-discovery learning.

The present chapter concentrates on exploratory learning. Learning processes involved will be described and compared with learning processes that we identified in a non-exploratory environment: studying texts. It is generally recognized that exploratory or discovery learning is a complex and demanding task and it therefore seems necessary to offer the learner support in order to ensure an effective and efficient study process. After describing some of the problems exploratory learning might pose to learners we will give some examples of support for learners involved in exploratory learning. Research into providing this support by a computer environment is the topic of a DELTA project called SIMULATE.

The SIMULATE Project: Providing Support to Exploratory Learning

Our work is part of a project called SIMULATE. SIMULATE (SIMulation Authoring Tools Environment) is an EC sponsored DELTA project that started in April 1989. The project has as its ultimate goal developing an authoring tool that will enable an author to create what we have called an Intelligent Simulation Learning Environment (ISLE). An ISLE is a simulation embedded in an environment that includes a diversity of types of support.

The present phase of the project (with a duration of two years) is envisaged as a preparatory phase that aims at gathering information and defining requirements and (global) specifications of both SIMULATE (the authoring tool) and ISLEs (the systems that will be built). A description of the project set-up is given in [17].

One of the starting activities in the project has been to make an inventory of potential elements of ISLEs. Since we see ISLEs as Intelligent Tutoring Systems we classified elements of ISLEs into one of the four 'classical' components of ITSs: *domain*, *learner*, *instructional strategy* and *learner interface*. As a second organiser we identified four characteristics of instructional use of simulations: *simulation models*, *learning goals*, *exploratory learning processes* and *learner activity*. By combining characteristics and components we could assess the consequences of having simulations as the core of an ITS. The results of the inventory are organised in a matrix of which the four characteristics of instructional simulations make one axis, and the ITS design components are at the other axis [for the complete overview see 6].

A second starting activity in the project was to create an inventory of authoring tools and means that could be used for creating different components of future ISLEs (for example, an inventory of all kinds of simulation construction tools has been made) and is reported in [39].

The present chapter will offer a selection and summary of the overview on elements of ISLEs and will concentrate on one of the characteristics of instructional use of simulations: the elicitation of exploratory learning processes. First, however, we will outline the four characteristics of instructional use of computer simulations.

Computer Simulations in an Instructional Context

The term 'simulation' is used for describing a wide variety of different situations, also within an instructional context. It seems necessary therefore to start with a more precise view on the instructional use of computer simulations. As described elsewhere [5], instructional use of computer simulations can be characterised by the following four features:

a. *Presence of formalised, manipulable underlying models*
   Computer-based simulation means that a phenomenon, a process, a system or an apparatus (or whatever it is that is being simulated) is *formalized* into a model and implemented as a computer program. This model may have a qualitative character, or a quantitative one, or both. It is essential that the output of the program is *calculated* or *inferred* from the implemented model in response to input from the learner.
b. *Presence of learning goals*
   Second, the simulation has to be used in the context of reaching a certain *learning goal*. These goals can be of different types: *conceptual knowledge, procedural knowledge,* which might be cognitive skills (e.g., problem solving in a specific domain) or skills with a psychomotor aspect (e.g., learning to fly), and *knowledge acquisition skills* related to the exploratory study process that takes place while learning with the simulation.
c. *Elicitation of specific learning processes*
   Third, the simulation must be used to invoke specific *learning processes* characteristic of exploratory learning. The path to the learning goal thus leads through these learning processes, such as hypotheses generation, predicting, and model exploration.
d. *Presence of learner activity*
   Fourth, there must be some level of *learner activity*. This means that the learner must actually *manipulate* something within the simulation, for example setting input variables and parameters, collecting data, making choices in a procedure, setting data presentations, or controlling simulation time.

Together, these four characteristics describe the instructional context of interest to us. A closely related type of instruction/learning is *modelling*. In modelling the learners are not only allowed to change values in the underlying model, but they may also interfere with the properties of the underlying model.

Exploratory Learning

Despite the fact that simulations are popular there is a general feeling that still much needs to be known about the exploratory (or scientific discovery) study process, or as Lesgold [23,

p. 325] says: '*We lack a good theoretical account of the process of scientific discovery....*' Fortunately, there is a number of recent studies that help chart this process [11, 19, 21, 23, 32, 36].

Learning processes

What became clear from Langley's et al. [21] detailed analysis of the process of discovery learning is its complicated and demanding nature. Klahr and Dunbar [19] and others stress that discovery encompasses two basically different processes: hypothesis generation and experimentation. Schauble et al. [32] emphasise that in scientific discovery learning, knowledge structures and discovery processes interact in a complicated way. This is important, given the fact that learners often have an incomplete and faulty knowledge base [see also 30]. If we are going to try to help learners in exploratory learning environments, we first need to know what is going on in the exploratory study process.

To start we distinguish two levels: the complete process of acquiring knowledge in a specific situation and the more detailed processes from which this knowledge acquisition process is composed. In this contribution we will denote the complete process as the *study process* and the detailed processes as *learning processes*. In describing the learning processes a similar approach to the one followed by [10] is taken, and detailed processes are categorised into more global and comprehensive processes.

The inventory of learning processes involved in an exploratory study process that we adopted in the SIMULATE project was developed on the basis of existing studies [e.g., 19, 22, 30], and two empirical studies [26, 27]. In the empirical studies we observed learners working with a computer simulation on control theory in mechanical engineering. Subjects (second and third year University students) had to think aloud while learning with the simulation. Along with the simulation the students received an assignment that prescribed a number of steps to be taken.

We do not see the resulting inventory as *the* conclusive set of exploratory learning processes, but it is regarded as a sensible basis for further work within SIMULATE. The list of processes will receive elaboration, more detail and possibly restructuring as research is continuing. Table 1 presents a summary of our inventory of exploratory learning processes.

Table 1
Exploratory learning processes

TRANSFORMATIVE PROCESSES

Analysis:
Analysis concerns charting the domain information. This learning process is subdivided into:

- *Looking for or finding information*
  The learner tries to find domain information by searching in text books, additional material, asking a tutor etc.
- *Model exploration*
  Identifying and relating variables and parameters in the model and indicating general properties of the model. This can be done on the basis of prior knowledge, additional material, but of course also from running the simulation.

Hypotheses generation:
Hypotheses generation is the formulation of a relation between one or more variables (input and output) and parameters in the simulation model. A hypothesis is stated with the intention to test it.

Testing:
Testing involves those activities that are necessary for furnishing data on which the learner expects to be able to accept or refute a new hypothesis, or to create an hypothesis. It consists of the following subprocesses:

- *Designing an experiment*
  Indicating what will be changed in a simulation model and in which order.
- *Making predictions*
  A prediction states the expectation of a simulation run outcome as the result of designated value attributions to variables.
- *Learner activities*, such as changing variable values, etc.
- *Data interpretation*
  Interpreting the data 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) or at a conceptual level by comparing output to other output that is known or to information from other sources.

Evaluation:
In evaluation results are put into a more general context. This process consists of:

- *Evaluating/Judging*
  Here the actions of the learner and the results thereof are evaluated (e.g., "I shouldn't have done this experiment.").
- *Generalising*
  In generalising the learner puts his/her 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

Planning:

In Table 1 a main distinction is found between *transformative* and *regulative* processes. The three *regulative* processes that we distinguish are *planning, verifying*, and *monitoring*. Transformative processes relate to processes in which domain information is transformed into knowledge. In the transformative class we distinguished: *analysis, hypotheses generation, testing*, and *evaluation*. These classes of learning processes are similar to those identified by others [for example 11, 12].

The learning processes in Table 1 are arranged in a certain more or less logical order. This is not necessarily the order in which they occur in exploratory learning. The inventory of learning processes should be regarded as a list of exploratory learning processes that can be applied in different sequences. So, for example, a learner who is an 'experimenter' [see 19] would first apply the process 'learner activity' and subsequently the process 'model exploration'.

A comparison to non-exploratory learning processes

We can get an impression of crucial aspects of the exploratory study process by comparing the learning processes, as identified and applied in our studies on exploratory learning (see Table 1 and [26, 27]) with the results that were obtained by Ferguson-Hessler and de Jong [10] in their investigation of learning processes when studying text. In the latter study subjects were offered a ten page text on a physics topic (the Aston mass spectrometer). The text was divided into small parts and after each part learners were asked to tell what they had done in the period before it. Analyzing these statements led to the identification of 32 different learning processes classified into main categories of which *superficial processing* (such as 'taking for granted'), *integrating* (bringing structure into new knowledge) and *connecting* (relating new knowledge to previous knowledge) were the important ones.

The first difference that becomes apparent from comparing the two learning processes inventories is that in the text processing list no explicit reference to *regulative* processes is made, whereas this is a main category for exploratory learning. Njoo and de Jong [27] report that up to 38% (with a mean of about 33%) of student's learning processes fall into this category. One of the subprocesses of regulation, *verifying*, as identified for exploratory learning has its counterpart in text processing where learners may check or verify derivations as they are given in the text. The subprocess *monitoring* from the exploratory learning processes list can be retraced to, for example, a study text learning process such as 'deciding that one can follow a deduction or derivation', but no general monitoring categories are indicated in the list of text study learning processes. *Planning* is a process that is absent in the text processing inventory. The only process that somewhat suggests planning is 'Quickly glancing through the text at the beginning of the studying to gain a first impression of major points and general structure of the text.' Although our text processing study was not directly aimed at finding regulative processes, we may conclude that, apparently, study texts can be rather imperative and prevent learners from making their own strategy of learning. In our studies on learning with a simulation on control theory we found that (even with learners who were generally reluctant to show exploratory behaviour) planning processes are quite important. The percentage of planning processes compared with the total number of processes applied ranged from 7 to 20% [27].

Another important aspect of exploratory learning is *model exploration* and *hypotheses generation.* Here learners *actively* construct their view of the domain. In our text processing inventory we find a number of processes that are characteristic of knowledge structuring. These are, for example, 'Confronting the text with other ideas or arguments, doubting the correctness of the text, generating alternatives for information from the text', 'Drawing conclusions', 'Finding relations oneself', and 'Imposing structure not given in the text'. A text processing category such as 'finding contradictions between one's own conclusions or between one's own conclusions and information from the text' comes very close to the exploratory process of testing an hypothesis.

There is some overlap between our inventories of exploratory learning processes and learning processes involved in studying text. In the latter study we compared the behaviour of good and poor performing students. It is interesting to see that the processes from studying text that seem to be present in exploratory learning (and that we labelled 'deep' processes in our study text research) are mostly found with good performers, whereas poor performers perform these processes less frequently [10].

Summarising, we can say that exploratory learning compared with studying text seems to call upon a broader range of learning processes. Also, the processes involved in studying text that have an analogous character to exploratory learning processes were found to be performed more frequently by good performers. This implies that a learning environment that asks this kind of behaviour explicitly from learners may produce major obstacles for the less proficient learners.

Potential problems in exploratory learning

A careful analysis of the exploratory study process will reveal the necessary ingredients of exploratory learning. In addition to this, in order to design effective and efficient support, we require an analysis of unproductive exploratory behaviour. Many studies report only that exploratory learning is difficult, but fail to indicate why and how. The comparison of text studying and exploratory learning from the preceding section suggested that weak students in particular will experience difficulties in exploratory learning, and this assumption is supported in literature [e.g., 23, 38].

Potential problems can be categorised with the help of the inventory of exploratory processes as listed in Table 1. Some problems that students encounter are related to a single *transformative learning process*. It is, for example, generally recognised that processes such as *model exploration* may benefit from the learner's prior knowledge [see for example 15]. This is also the reason that we found that a large percentage (means of 12 and 20 %) of students' learning processes may be concerned with looking up information [26, 27]. Schauble et al. [32] found indications that learners' knowledge also influences the strategy that they use in exploratory learning. Lavoie and Good [22] report unsuccessful prediction behaviour correlates with low prior knowledge.

Hypothesis generation is another process that might pose problems to learners. Shute and Glaser [36] state that learners do not recognise that apparent regularities in data need to be tested with hypotheses. Van Joolingen and de Jong [42] found that learners are prone to state either too global or too complicated hypotheses.

According to Reimann [30], who observed learners interacting with a microworld on optical refractions, learners do not *design experiments* systematically. Shute and Glaser [36] found that learners (especially the poor ones) do not vary one variable at a time and thus fail to detect important domain relations, a finding also reported by Lavoie and Good [22], and Schauble et al. [32]. Schauble et al. [32] also found that unsuccessful and successful exploratory learners are equally active in their behaviour, a finding that was also reported for studying text [10].

Data interpretation may also provide major obstacles to students. Many computer simulations present their data as graphs, and graph interpretation appears to be problematic, especially for children [24, 25]. We also found that data interpretation is still not easy for university students [26].

Another group of problems relates to the *connection between (the results of) different learning processes*. One of the most remarkable findings is that learners seek for confirmative evidence. They tend to keep hypotheses despite disconfirming information, and they even reject hypotheses for which they have confirming evidence [19]. In a study of students working with a computer simulation in chemistry (chemical titration), van Joolingen and de Jong [42] found that students quite often do not design experiments suited to test the hypothesis that they stated. Shute and Glaser [36] found that good performers tend to base their conclusion on adequate and sufficient evidence, whereas poor performers tend to rely on inadequate data. They also conclude that poor performers quite readily accept a at first sight correct statement about their data, even if this statement is not completely adequate. This is in line with the finding of Ferguson-Hessler and de Jong [10] that poor learners more easily accept a finding without taking the trouble of questioning it.

Finally, an important source of difficulties that learners experience is in the area of *regulation*. Some authors emphasise that exploratory learning with computer simulations is a complex process and students seem to underestimate the complexity [32]. This is a phenomenon we also found for student learning with a computer simulation on decision support theory. where students made no notes despite the fact that they were offered dedicated forms to do so [7]. Shute and Glaser [36] comparing poor and good performers in learning with a microworld on economics, found that successful students use more thinking and planning skills. These learners use more global (across a number of experiments) planning, whereas the planning of poor performers has a more local (within one experiment) character. Similar results are reported by Schauble et al. [32]. We found that learners even tend to restrict planning to stating what they will perform as an immediate next action, and fail to perform any form of global planning at all [26, 27].

Supporting Learning Processes

The preceding section indicated some difficulties that students may encounter when working in an exploratory, computer simulation, environment. A next step is to search for ways to overcome these difficulties.

First, one may explicitly train learners in exploratory or scientific inquiry skills. Examples of such training programmes are given in [11] and [12].

A second approach is to support the learner while s/he is working with the simulation. Generally, this support is given by a human tutor, but it can be provided by a computer environment as well. In this way, the plain simulation is combined with other forms of instruction as is advocated by [9]. There is now a number of systems that present the learner a simulation along with some kind of support. Some of these systems are: QUEST (troubleshooting of simple electronic circuits; [44]), STEAMER (operating a steam propulsion plant; [18]), MACH-III (maintenance and trouble shooting of a complex radar device; [20]), IMTS (troubleshooting in complex devices; [40]), and Smithtown (micro-economics; [36, 37]).

In providing support we can make a distinction between *directive* and *non-directive* support. *Directive support* (or guidance) steers the learner in a certain direction. In this way it guides the learner, for example when the learner gets direct feedback and/or hints on directions to follow. Especially when the learning goal involves some kind of procedure, the learner's action sequence can be traced. When it diverges from some normative sequence, the learner can be corrected [see for example 20]. Hints such as 'it is better to change only one variable at a time' [31, 36] and hints on where in a device to search for a fault [40] are also examples of directive support. A survey of directive support can be found in [41].

Non-directive support, does not steer the learner in a certain direction, but helps with accomplishing what s/he would have done in a completely free exploratory environment. We have called these kinds of tools *learner instruments*, of which examples are *dedicated scratchpads*: scratchpads that are meant to support a specific learning process. Hypotheses scratchpads are such dedicated scratch pads. Different forms exist. The more structure the 'scratchpad' has (e.g., a list of predefined hypotheses) the more directive it is [for a discussion of different types of hypotheses scratchpads see 4]. Other examples of learner instruments are 'notebooks' for recording intermediate results [36]. Finally, we have genuine 'scratchpads', empty spaces the learner can use to note down anything s/he likes. These scratchpads do not support specific learning processes but have the general aim of reducing the working memory load.

The distinction between directive and non-directive support is not clear. Somewhere in between directive and nondirective support is *putting restrictions on the simulation environment*, for example when certain parts of the underlying model are not accessible to the learner, when the range of possible values to give to variables is restricted [2], or when learners are presented with a sequence of qualitatively different models to explore [13, 29, 44]. A recent study by Veenman and Elshout [43], however, doubts the advantage of structuring exploratory environments in this way.

The space of possible actions of learners can also be restricted by offering them an *assignment* that suggests a particular problem (e.g., optimisation or fault diagnosis) to solve with a computer simulation. We have, however, the experience that this sometimes inhibits exploratory learning [26] which might be difficult to overcome even by introducing hints that stimulate exploratory behaviour [27].

Finally, learners can be supported in planning and monitoring their study process. In a present study [28] we offered learners, who were using a computer simulation in control theory, forms to work on that had separate areas for the different transformative processes as given in Table 1. In this way, learners are encouraged to follow a complete exploratory study process, and they can easily monitor their own study process. In another ongoing study we are developing ways to provide learners with overviews of their interaction with a simulation on decision support theory [7]. These overviews present the learners with a summary of their interaction strategy with the simulation, and thus they offer a means of monitoring the study process. Providing overviews or navigation tools is currently a major research topic in hypertext based learning [14].

Conclusion

Exploratory learning with computer simulations is in the centre of contemporary interest. Despite this and despite the fact that numerous simulations are used in instruction, there is still not enough research that describes exploratory learning processes and even less research on how to support learners in exploratory learning. The present chapter attempted to give a summary of our present work on these topics, much of which is being performed within the context of the SIMULATE project.

There are two directions that we will follow in our future (empirical) research. First, we will continue to elaborate and restructure our inventory of exploratory learning processes. This will be done mainly by observing learners involved in exploratory learning in a number of domains. This also provides the opportunity for discovering empirically problems that learners encounter. Second, in accordance with the first objective, we will evaluate the effectiveness of a number of support mechanisms on exploratory learning. Examples of these are different forms of hypotheses scratchpads [42], study process guidance forms and ready-made hypotheses [28], and overviews [7].

In the SIMULATE project an effort is currently being made to find a more formal representation language for describing the information as gathered in our inventory work (of which a part was reported in the present chapter). In addition, we are attempting to identify basic conceptual units that have to be described in this language (or languages). This means that we will identify *generic* elements, relations and structures for each of the components of an Intelligent Simulation Learning Environment. The next step will then be to create building blocks for each of these components that authors may actually use to create ISLEs by means of *selecting*, *specialising* and *instantiating* [for a more detailed description see 8].

The final SIMULATE system is envisaged to consist of a permanent *shell*, filled with *default information*, containing the functionality of an ISLE that is always present, and *author generated information* [for a description see 16]. For providing this author generated information the author is supported by a library of building blocks of ISLE components as mentioned above, and further by a set of rules that constitute *recommendations* of good instructional design and a *methodology*. Information as collected in our inventory will play a crucial role in designing SIMULATE. As should be clear, however, creating a true SIMULATE authoring work bench lies beyond the reach of the present phase of the project.

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