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# Issues in computer supported inquiry learning in science

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Abstract

Computer supported inquiry learning has become an important application of computers in education. Computers allow for providing resources for inquiry learning, such as simulations; built-in support for the processes of inquiry learning; support for collaborative learning scenarios as well as tools for modeling by learners. An overview of the main issues on research on computer supported inquiry learning is provided including issues such as assessing learning effects of computer support, gaming learning systems, as well as conditions that are favorable or detrimental to learning. The articles in the current special issue are discussed with respect to their contribution to resolving these issues.

**Keywords** cognitive tools, inquiry learning, technology enhanced learning.

## Introduction

Current views on science learning state that this should not involve learning just about the established *results* of science, including well-established theories such as Newtonian mechanics or the evolution of species as well as important empirical discoveries such as Young's double slit experiment or the structure of DNA. Instead science learning should also focus on the *processes and methods* used by scientists to achieve such results. One obvious way to bring students into contact with the scientific way of working is to have them engage in the processes of scientific inquiry themselves, by offering them environments and tasks that allow them to carry out the processes of science: orientation, stating hypotheses, experimentation, creating models and theories, and evaluation (de Jong 2006a). Involving students in the processes of science brings them into the closest possible contact with the nature of scientific understanding, including its strengths, problems and limitations (Dunbar 1999). This is the main claim of *inquiry learning*: engaging learners in scientific processes helps them build a personal knowledge base that is scientific, in the sense that they can use this knowledge to predict and explain what they observe in the natural world.

For about the last 20 years, computers have been used to create environments that engage learners in scientific inquiry activities. The virtue of the computer is that it allows the scaling down of inquiry tasks to a manageable size for learners who are inexperienced with inquiry processes. There are several ways in which computers can help create challenging and manageable environments for inquiry learning:

- Replacing the natural world by a computer simulation can help make available on a wide scale the phenomena to be investigated. Moreover, the simulation may be simplified and/or emphasize certain aspects of the domain that can help learners observe critical features of the domain (van Joolingen & de Jong 1991a; de Jong & van Joolingen 1998; de Jong 2006a).
- The computer can offer tools that support the inquiry processes, such as tools to analyse or visualize data, tools that help learners state hypotheses and tools that

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help learners manage the learning process (van Joolingen 1999; Linn *et al.* 2004a; Quintana *et al*. 2004; de Jong 2006b).
- The computer can support collaboration between learners, allowing them to communicate, share data, results and ideas, and discuss consequences for the knowledge that is under construction (Okada & Simon 1997; van Joolingen *et al.* 2005).
- Computer-based modelling tools allow learners to express their theories in models that can be simulated. In this way learners can use their theories operationally, confronting themselves with the consequences of their ideas (Hestenes 1987; Schecker 1993; Jackson *et al.* 1996; Fretz *et al*. 2002; Zhang *et al*. 2002; Schwarz & White 2005).

Computers thus allow the creation of computer-based inquiry environments in which learners can engage in genuine inquiry tasks and thereby learn the domain together with learning scientific inquiry processes, in an environment that scaffolds them. The need for such scaffolding has been widely recognized, given studies in which 'free' exploration, that is offering computer simulations without any support, has been shown not to benefit learners (Klahr & Nigam 2004; Mayer 2004), whereas supported discovery learning with simulations has been shown to be an effective mode of learning (White & Frederiksen 1998; Hickey *et al.* 2003; Ketelhut *et al.* 2006). Therefore, current research in the field of inquiry learning focuses less on the effectiveness of inquiry learning *per se*, and more on how to provide the tools and the circumstances that are beneficial for inquiry learning.

In this introduction to this special issue on inquiry learning, we outline the current issues for research in the field. In this outline, in the form of a research agenda, we cover two research traditions which are currently merging: *scientific discovery learning* or *inquiry learning* (e.g. de Jong & van Joolingen 1998), focusing on the experimental side of science and *modelling* (e.g. Hestenes 1987), which takes the formulation of models and theories as its entry point. We feel that both traditions have a place in a more integrated view of the development of scientific knowledge and skills in the learning of science (de Jong & van Joolingen, in press). We therefore see computer-supported inquiry learning as including tools and methods originating from both viewpoints.

## Research on inquiry learning

One important finding in the field of research on computer supported inquiry learning is that inquiry learning needs support. This support may vary, and different forms may be more or less effective. The research agenda for the research field should be to build a knowledge base of the characteristics of different kinds of support, their effects and problems and the circumstances under which they are best applied. This knowledge should provide a foundation for the design of effective environments for inquiry learning.

## Support for learning processes

The first question when discussing support for learning processes in inquiry learning is what the processes are that need support. Traditionally, these processes have been derived from the 'inquiry cycle' of scientific research, going from orientation to hypothesis generation, experimentation, conclusion and evaluation. These *transformative processes* are controlled by *regulative processes* such as planning, monitoring and evaluation (of the learning process).

Support for learning processes typically takes the form of *cognitive tools* or *scaffolds*. The basic idea of most cognitive tools is to boost the performance of learning processes by providing information about them, by providing templates, or by constraining the learner's interaction with the learning environment. For instance, van Joolingen and de Jong (1991b) introduced a hypothesis scratchpad that offers a template that learners can fill in with relations and variables. Use is optional but when used, the scratchpad ensures that the hypotheses stated are testable. In this way, the scratchpad attempts to stimulate the process of hypothesis generation. Another form of support can be found in WISE (Linn *et al.* 2004b), where the learner is led through a sequence of steps that represents the inquiry cycle. Learners can only proceed to the next step when the previous one has been completed. This kind of process support constrains learners in their actions, preventing paths that may be detrimental for the learning process. A number of overviews of possible scaffolds and their effects have been presented recently (van Joolingen 1999; Linn *et al.* 2004a; Quintana *et al*. 2004; de Jong 2006b).

These two examples of scaffolding differ in two ways. One is optional, the other obligatory; in addition, one is stimulating, the other constraining. A major question is how to optimize support by balancing these two aspects in such a way that learning is supported effectively, but the inquiry process is not reduced to following cookbook instructions. In other words, support needs to leave room for learner freedom.

## Effects of support

When support is offered, for instance in the form of a hypothesis scratchpad, two levels of effects are expected. The *first order* effect is that the learning processes are better performed. In the case of using a hypothesis scratchpad, for example, more and better formulated hypotheses should result. The *second order* effect is that support should lead to a higher knowledge gain than when no support is offered. So, for example, if students can create better testable hypotheses with a hypothesis scratchpad this should ultimately lead to improved knowledge.

Second order effects for supported discovery learning have been observed in a number of studies, as mentioned above (White & Frederiksen 1998; Hickey *et al.* 2003; Ketelhut *et al.* 2006) as well as in Swaak and de Jong (2001), who found an effect of specific *assignments* on the development of intuitive knowledge and Gijlers and de Jong (in prep.) who found improved post-test scores as an effect of providing a list of predefined hypotheses that led collaborating learners to consider each other's ideas.

In a number of cases, first order effects did not result in second order effects. In such cases, effects of instructional support have been detected by means of log files, think-aloud protocols, or by means of intermediate learning products, such as learner stated hypotheses, but no effect in terms of improved post-test scores could be found. An example of this can be found in our own research on the hypothesis scratchpad (van Joolingen & de Jong 1991b, 1993; Saab *et al.* 2005). These studies compared different versions of the hypothesis scratchpad with each other and with a no-scratchpad condition. Offering structure within the hypothesis scratchpad in the form of preset relations and variables resulted in improved hypothesis generation processes, such as better stated hypotheses and more experiments that explicitly tested hypotheses, but when compared with a group and received no such support or a less structured version of it, no additional improvement on post-tests was found. In other cases (such as Veermans *et al.* 2000; Reid *et al.* 2003; Zhang *et al.* 2004; Veermans *et al.* 2006), the second order effects of support were found but were either small or of a complicated nature. For instance Veermans *et al.* (2000) found that support for experimentation strategy worked mainly for students with high prior intuitive knowledge.

A probable explanation for this may be that the support offered and the resulting improved learner behaviour need more time to facilitate knowledge building. In many studies such time is not given, as studies normally only stretch out over time spans of up to a few lesson periods. There is clearly a need to place our research designs at a curricular level, involving students in inquiry activities that take more than a few lessons. It should also be taken into account that the second order effect is expected to arise on top of a pre-existing knowledge gain due to the learning environment itself.

A second reason for a lack of a second order effect may be that the processes that are supported do not contribute to the knowledge building process. We can illustrate this with the example of the hypothesis scratchpad. Introducing a supportive tool means introducing an additional task, with its own structure and its own goals. The relation of the tool and the task may not be directly clear for the learner, and he or she may therefore ignore it, or use it (because it is offered) but not connect it with the discovery process. The task is presented for the learner by the learning environment, and we should not assume by default that the learner sees the inquiry task that is presented as the main challenge. Instead, learners try to meet the requirements posed by the learning environment, which may mean performing the activities suggested by the supportive measures; this is different from using the support to facilitate deeper insight into the process. The learner's goal then becomes 'completing the learning environment.' This means that an unwanted side effect of support is that it may divert the attention away from the inquiry process towards dealing with the support itself.

Having 'completing the learning environment' become the main goal for a learner may lead to 'gaming' the system (Baker *et al.* 2004). Gaming the system is defined as mainly performing actions that take you through the system with a minimum of effort, like trying to give answers quickly (with multiple choice questions: trying 1, 2, 3, 4 until the right one is found) and misusing help systems for the sake of finding the right answer quickly, without the intention of learning.

Research should be directed at detecting the circumstances that lead to this kind of behaviour and to the design of support that makes this less likely. A working hypothesis is that the more the support is integrated into the basic processes of inquiry itself, the better its effect and the less the danger of 'gaming' and related behaviour. One possible way to achieve this is to have learners create artifacts, such as models, concept maps, or designs, as a result of their work, and to design the support in such a way that it is integrated within the process of creating these artifacts. So, for instance, the hypotheses on the scratchpad may be directly built into a model. Another way may be to build the support into the means of communication with teachers or fellow learners. In other words, support should be built into the primary cycle of work. How to do this is a question that may provide inspiration for research for a long time to come.

## Learning conditions

Apart from looking at the inquiry learning environment itself, there are several other factors that influence the learning process, and that need to be investigated. Some of these factors are related to the *learner*, and some to the *context* in which the learner encounters the environment.

It would be too much to mention all possible learner characteristics that are relevant in this context, but we can distinguish personality traits, prior knowledge and motivation. Only a few studies have dealt with inquiry learning and personality traits. One example is a study by Leutner (1993) on anxiety and inquiry learning. More is known about prior knowledge, and we can identify a number of types of prior knowledge that seem to be important (de Jong *et al*. 2005). First, there is the prior domain knowledge learners bring to the learning environment, which will influence the paths they take in the environment. It will influence the hypotheses stated, the initial models created and the experiments designed. Learning environments can utilize prior knowledge by having learners making their knowledge explicit in terms of a set of propositions (Gijlers & de Jong, submitted) or an initial model they construct (Krajcik *et al*. 1998). These initial expressions of knowledge can then be used to build upon, or to help identify misconceptions that must be broken down before building up new insights (Posner *et al.* 1982).

Apart from domain knowledge, learners also bring prior process knowledge to the learning environment. For instance, *inquiry skills* are an obvious kind of relevant prior knowledge. Knowing how to perform inquiry learning processes will have a positive influence on the outcome. One interesting question, however, is whether the structure of the domain interacts with the skills of inquiry; in other words, to what extent are inquiry skills domain specific? Related but not identical are the *epistemological beliefs* that learners possess (Hogan 1999; Hogan & Thomas 2001). In modelling environments especially, one may expect a relation between learners' concepts of the role of scientific knowledge, theories and models and their processes in constructing such models. It presumably makes a difference when a learner seeks for an absolute truth rather than trying to find a particularly useful model. Sins *et al.* (in prep.) found some initial evidence of such a relation in which learners with a higher level epistemological understanding (i.e. a better understanding of the roles of theories and models in science) carried out more 'deep' and fewer 'surface' processes, meaning that they involved their prior knowledge and the knowledge they gained during the inquiry process better in their reasoning. Learners' *motivation* plays a role as well in inquiry. Literature shows that motivation influences learning in almost all contexts (e.g. Pintrich & de Groot 1990; Bandura 2001). With regard to inquiry learning specifically, Saab *et al.* (in prep.) as well as Sins *et al.* (in prep.) have found a relation between task orientation motivation and deep processes of learning, such that the more the learner is focused on performing the task, the more he or she will use 'deep processes' in the inquiry task.

Factors in the *context* of learning include the role of the teacher (Kirschner 2001) and the social and technological infrastructure (Lipponen & Hakkarainen 1997). The role of the teacher is a factor that is especially influential. The facilitation of practices of inquiry also requires support for teachers (Lipponen & Hakkarainen 1997), and systematic research on supporting the teachers' role in inquiry-based science learning is needed (Brown & Edelson 1998; Edelson *et al.* 1999). A few interesting examples exist, like those of Tabak (Tabak 2004) who proposes 'synergetic scaffolding' that brings together software features designed for scaffolding and teachers' scaffolding activities. However, further research is needed to identify what properties of the interactions make such synergies fruitful or not. A related critical factor is the way the learning activities are designed. Curricular activities and materials are important media through which teachers, students and tools interact. An appropriate sequence of activities seems to be critical for students' learning, for example, activating the motivational aspects (e.g. addressing an open or controversial scientific issue), as well as triggering appropriate cognitive operations (Trumbull *et al.* 2005). Moreover, designers of learning activities need to understand how teachers in different settings think about the pedagogical affordances of inquiry learning environments. They must have a sense of the different types of tasks teachers will find useful, understand the various learning objectives that teachers seek to achieve, be aware of the different methodologies and classroom management techniques that will facilitate use in the classroom, and must be aware of the diverse goals, objectives and motivations that teachers and students have when investigating data.

## Individual and collaborative inquiry

Collaborative inquiry learning is another growing area of research. (Okada & Simon 1997; Hakkarainen *et al.* 2001; Kaartinen & Kumpulainen 2002). Collaboration is very natural to real scientific inquiry, so the introduction of collaboration into the learning process brings the learning environment closer to real inquiry. This focus on collaborative inquiry also arises due to reasons related to the learning process, having to do with the developments mentioned above. One reason is the recognition that support in the inquiry process can come from fellow learners instead of or in addition to cognitive tools. One student's stronger inquiry skills may compensate for the weaker skills of another. The second reason is that students may differ in prior domain knowledge; this difference may raise a challenge for the inquiry process (Gijlers & de Jong 2005, in prep.). A research issue for the field is to find ways of adequately supporting communication and the collaborative knowledge building process in collaborative inquiry learning, possibly with the help of collaboration scripts (Weinberger *et al.* 2005). A close understanding of collaborative inquiry processes is necessary in order to develop this kind of support.

## Assessing learning products

The end product of any learning process should be a permanent change in the knowledge of the learner. This means that in investigating inquiry learning we should not only look at the process of inquiry, but also to its result. A basic question is 'What do we expect to be learned from inquiry learning?'

Swaak and colleagues (Swaak & de Jong 1996; Swaak *et al.* 1998; Swaak *et al.* 2004) have attempted to measure *intuitive* knowledge in the context of learning with computer simulations. This has led to the so-called 'what if' test that elicits learners' intuitive responses to situations in the domain. With respect to modelling, the focus has been mainly on the way of thinking induced by the modelling task. An assessment for 'system thinking' skills is available (Booth Sweeney & Sterman 2000). This assessment tests whether learners are capable of approaching a given system in a way that facilitates modelling. More work is needed to include also the domain-specific knowledge that is constructed in modelling tasks. After all, the idea behind modelling is that by constructing a model, learners learn to predict and explain the behaviour of the domain. Attempts are currently underway to design tests that assess this kind of domain-specific knowledge (van Borkulo & van Joolingen, in prep.).

Research results from various inquiry learning approaches suggest that the lack of explicitly defined assessment criteria at the beginning of the course can cause problems for students in the inquiry process (White *et al.* 1999; Lakkala *et al.* 2002). Providing students with criteria for understanding the goals of learning and assessment is essential. Moreover, when the inquiry process involves collaboration, it is important to employ both individual and collaborative assessment (Lee, Chan, & van Aalst 2006). In this case, the notions of self and peer assessment seem promising. This means a turning over of the responsibility of assessment to the student as well as to the group as a whole, so as to develop increased agency as students evaluate their own learning progress.

## The current issue

The research agenda outlined above covers the spectrum of possible research in the field of inquiry learning.

The current special issue offers four articles[1] that each address issues within this agenda, although it is obvious that they can cover only a small part. In the current section we will discuss these contributions in the light of our agenda.

Zacharia (2007) has studied the effect of introducing a simulation instead of a real laboratory in the domain of electric circuits. He replaced a real lab with a virtual lab in an inquiry-based curriculum, so that for part of the time students worked with a simulation instead of the real electronic components. Without doing anything extra, the students with the virtual lab outperformed the ones using the real laboratories. The conclusion to be drawn is that the computer support for inquiry in the form of a simulation pays off in this context. Based on what we said above, this may be explained by the reduced cost of experimentation within the learning environment when using simulations. A follow-up study could investigate whether improved experimentation is indeed the cause of this improvement. It is interesting to see in this paper that the author was very cautious in replacing the real lab with a virtual one, doing this for only part of the curriculum and also paying much attention to potential drawbacks. The result proves that in the future we may feel more free in making such replacements, unless, of course, the physical laboratory manipulations themselves are the object of instruction. The virtual lab must also provide at least the same amount of information as the real lab. An extra advantage is that instructional support can be woven into the simulation. Finally, an important feature of Zacharia's study is its placement within an intact curriculum.

Wecker, Kohnle and Fischer (2007) studied the influence of a specific type of prior knowledge, computer literacy, on learning in inquiry environments. Computer literacy was found to have an effect, but not in the way that was expected. Less computer literate students learned more from the inquiry environment, which is indeed a surprising result. The authors conclude that computer literacy seems to lead to less functional behaviour with respect to knowledge acquisition. This is illustrated by the fact that these more computer literate students find their way faster through the environment, but apparently learn less along the way, something that may be similar to 'gaming' the system as discussed in the first part of this introduction.

Papaevripidou, Constantinou and Zacharia (2007) address the utility of modelling for learning about ecosystems. They chose Stagecast Creator as a tool, which is a non-standard choice for a modelling tool. Whereas many tools such as STELLA (Steed 1992) based themselves on conceptual models, Stagecast Creator models individual objects, which provides a different perspective on the modeled system. The use of Stagecast Creator is compared to worksheet-based instruction. Use of the modelling tool contributed to typical modelling skills, such as formulating models and extracting information from them. The main lesson from this study is that making models yourself helps you to appreciate their value. Over the long-term, this should lead to a better appreciation of the value and limits of scientific knowledge and the nature of science.

Finally, Ergazaki *et al.* (2007) analysed the processes of learners who collaboratively built a model of a biological system. The main finding of this study is the development of a vocabulary to describe modelling processes and to distinguish several modes of modelling. Another important notion in this article is the role of the modelling tool in the *process* of modelling. Instead of being a tool for expressing a mental model, it is a tool for *building* a mental model. This emphasizes the potential for seeking supports that can be integrated within the primary process of model building in the modelling tool.

## Conclusions/outlook

Together these four articles provide new building blocks for the body of knowledge on inquiry learning. They cover various aspects of the grand agenda for discovering the ways of involving learners in effective inquiry learning. Like most studies they provide some answers but also new questions. The most puzzling questions seem to be related to the students' perception of the learning environment. How do they perceive the task? Can we prevent students from 'gaming' the system and can we weave support into the primary loop of execution without becoming too invasive? The studies presented here, in particular the Wecker study, but also

[1]These papers are based on a selection of presentations from a workshop of the SIG 'Computer Supported Inquiry Learning' of the Network of Excellence 'Kaleidoscope'. This workshop was held in Genoa Italy, May 2005, and was partially funded by the Kaleidoscope European Network (European community contract number NoE IST-507838). More information on the SIG 'Computer Supported Inquiry Learning' can be found at: http://csil.noe-kaleidoscope.org. More informationon Kaleidoscope can be found at: http://www.noe-kaleidoscope.org/

those by Zacharia and Ergazaki put this question higher on the research agenda.

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