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Multi-Level Support With Respect to Inquiry, Explanations and Regulation During an Inquiry Cycle

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Astrid Wichmann
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Prof. Dr. Detlev Leutner
Prof. Dr. Ulrich Hoppe

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Abstract

Engaging students in inquiry learning without sufficient support often results in poor learning performance. Students need to be supported to benefit from inquiry learning activities (de Jong, 2006; Hmelo-Silver, Duncan, & Chinn, 2007). The main goal of this work is to investigate the effects of supporting regulation using prompts on learning gain and scientific reasoning in a computer-based inquiry learning context offering advanced inquiry support. Does learning gain depend on the extent of inquiry support? Are regulation prompts (e.g. "Compare your result graph with your hypothesis. Are they different from each other?") superior in comparison to generic explanation prompts (e.g. "please explain") with respect to knowledge gain and scientific reasoning? Do students benefit from those additional regulation prompts sustainably? Before these questions were addressed in two experimental studies, an exploratory study revealed problems to engage in (1) deliberate regulation and (2) a tendency to write descriptive explanations lacking scientific reasoning while running experiments in an inquiry cycle. The model-based environment FreeStyler (Hoppe & Gassner, 2002) was adapted to guide a learner through the respective phases of an inquiry cycle and to offer prompts. Results of the main experimental study were able to confirm findings from the pilot study showing an advantage for the regulation group (students receiving regulation prompts) in comparison to the explanation group (students receiving explanation prompts only) with respect to knowledge gain. In addition, it was shown that the regulation group outperformed a basic inquiry group that served as a baseline receiving minimal support in terms of inquiry and no support with respect to explanation and regulation. Moreover, the sustainability of this effect was demonstrated. It was shown that prompts are effective means leading to deeper processing and that explanation prompts should be augmented with regulation prompts. Findings suggest in general that in order to engage learners in inquiry learning, a balance between inquiry support, explanation support, and regulation support is needed.

Zusammenfassung

Das Lernen durch Experimentieren (Inquiry Learning) ohne eine geeignete Unterstützung führt oft zu schwachen Lernergebnissen. Um mit den Anforderungen, die sich durch das Experimentieren ergeben adäquat umzugehen, muss dem Lernenden eine geeignete Unterstützung angeboten werden (de Jong, 2006; Hmelo-Silver, Duncan, & Chinn, 2007). Hauptziel dieser Arbeit ist es, zu untersuchen, inwiefern die Unterstützung von Regulation mithilfe von Prompts eine Auswirkung auf das Wissen und Schlussfolgern von Schülern im Bereich des Experimentierens hat. Hängt der Lernzuwachs vom Ausmaß der Unterstützung beim wissenschaftlichen Experimentieren ab? Sind Regulationsprompts (z.B. "Vergleiche dein Ergebnisdiagramm mit deiner Hypothese. Unterscheiden sie sich?") in Bezug auf Wissenszuwachs und wissenschaftliches Schlussfolgern besser geeignet als einfache Erklärungsprompts (z.B. "Bitte formuliere eine Erklärung")? Profitieren Schüler nachhaltig von den zusätzlichen Regulationsprompts? Der Auseinandersetzung mit diesen Fragen wurde eine explorative Studie vorangestellt. Die Ergebnisse dieser Studie zeigten, dass Schüler erstens Probleme haben in geeigneter Weise ihr eigenes Denken und Lernen zu regulieren und zweitens eine Tendenz aufweisen, mangels wissenschaftlichen Schlussfolgerns oberflächliche Erklärungen zu formulieren. Die computerbasierte Lernumgebung FreeStyler (Hoppe & Gassner, 2002) wurde weiterentwickelt, um den Lernenden durch die Phasen eines Experimentierzyklus zu führen und Prompts an geeigneter Stelle darzubieten. Ergebnisse der Hauptstudie bestätigten Ergebnisse aus der Pilot-Studie, wonach sich für eine Regulationsgruppe (Darbietung von zusätzlichen Regulationsprompts) im Vergleich zu einer Erklärungsgruppe (Darbietung von Erklärungsprompts) ein Vorteil bezüglich des Wissenszuwachses ergibt. Zusätzlich konnte gezeigt werden, dass die Regulationsgruppe bezüglich des Wissenszuwachses besser abschneidet als eine Inquiry-Gruppe, welcher minimale Unterstützung bezüglich des Inquiry-Prozesses und keine Unterstützung bezüglich Regulation und Formulierung von Erklärungen dargeboten wurde. Außerdem wurde die Nachhaltigkeit dieses Effektes

für das wissenschaftliche Schlussfolgern nachgewiesen. Die Ergebnisse weisen darauf hin, dass Prompts zu einer tieferen Wissensverarbeitung führen und legen die Empfehlung nahe, dass Erklärungsprompts durch Regulationsprompts angereichert werden sollten. Zusammenfassend lässt sich feststellen, dass es einer ausgeglichenen Unterstützung auf mehreren Ebenen bedarf, um das Lernen durch Experimentieren zu fördern. Dies sollte eine Unterstützung sowohl während des Experimentierprozesses als auch während des Erklärens und der Regulation des Lernprozesses beinhalten.

Acknowledgements

Most and above all, I want to express my gratitude to my advisor Prof. Leutner, whose critical remarks and patient support I could always rely on. With his expertise, he taught me to sharpen my focus from broad questions to testable research questions and to describe the design of a study as clear as possible. I would like to acknowledge the support of Prof. Hoppe who helped me to venture into my current field of educational technology. He provided me with excellent people who helped me to adapt and to use exciting technology in the classroom.

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Finally, I would like to thank my family for their undying support. Most specially, I thank Thomas Ottmar for still being around. Dombart, you are the gravity my life circles around.

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A Note on the Quotes

At the beginning of each chapter, you will find a quote. Every quote includes an explanation that was articulated by one of the students taking part in one of the three studies. The explanations have been developed during different phases of an inquiry cycle. The students were running three inquiry cycles investigating biomass production in the context of “humans living on a remote planet”. In the first cycle, students were investigating the effect of light on plant growth. In the second cycle, students were changing the variable carbon dioxide to observe effects on plant growth. In the third cycle, students were looking at the interaction of two factors carbon dioxide, and light. Some of the explanations are impressively complex and some are just fun to read. I hope you find them as inspiring as I did.

"I think that the edible biomass will increase until it reaches saturation. Because the plant doesn't need CO_2 and then the plants closes its stomata. Maybe the stomata gaps close because of the pressure inside it."

(Student from Katedral School, Sweden)

1 Introduction

Current efforts in supporting science learning have been focusing on instructional approaches that engage the learner in active knowledge construction. One approach that has been receiving much attention is inquiry learning. Inquiry learning is an accepted approach to design activities that bring students closer to science. It has been promoted as an instructional approach that situates learners in complex activities (Hmelo-Silver, Duncan, & Chinn, 2007). These activities include posing questions, which can be tested subsequently, developing hypotheses, gathering and analyzing data and using newly gained knowledge to pose new questions. Such activities need to be guided to enable learners to accomplish tasks successfully. Inquiry learning, as opposed to unguided inquiry, provides support, which allows learners to engage in activities that they would not accomplish otherwise (de Jong, 2006). Recent developments in computer-based inquiry environments offer activity structures helping learners to make complex tasks manageable. Activity structures facilitate learners to follow a systematic workflow, by keeping track of the material produced or by providing macro-level structures, which guide the learner through a sequence of tasks. In addition, computer-based environments can take over routine tasks, simplify tasks, and allow the learner to focus on aspects that are relevant for learning. Inquiry support is an indispensable ingredient of inquiry learning; however, it alone does not engage learners in deep processing. Inexperienced learners tend to go through the motions of an inquiry cycle without reflecting on the experiences made and the new evidence gathered (Kuhn & Pease, 2008). Encouraging students to explain their thinking can lead to the reflection that is needed to turn inquiry into a meaningful, meaning-making activity. Yet, reflection per se does not equip students to coordinate their learning autonomously. Students need to take executive control to coordinate flexibly new evidence and experiences with their existing understanding.

This coordination is part of a scientific reasoning process, which is represented in students' explanations. Therefore, an essential part of inquiry learning should be to support learners in regulation. In sum, the most challenging part of designing inquiry environments is to get the balance right between inquiry support, explanation support and regulation support.

"The plants take up the CO_2 from the surrounding air, this happens mainly during day time since the light is slightly brighter then than during night time. When the CO_2 is taken up by the plant, it is pure logic that it decreases from the air, which is very good for us human beings since it is toxic for us when we get too much. The plant transforms the CO_2 into O_2, which is one of the waste products from the photosynthesis. So, my conclusion is that the more CO_2 the plant takes up and then transform it into O_2 the better for our nature and ourselves. Although I don't think the plant can take an unlimited amount of CO_2, therefore we need to be careful to what we do with our nature and think before we let too much CO_2 out in to the air."

(Student from Katedral School, Sweden)

2 Theoretical Framework

2.1 Inquiry in Classroom Science Learning

The demands in today's school system, especially in the field of science, increase with the knowledge and the scientific discoveries being made. Every year, the curricula in Physics, Chemistry, and Biology become denser to provide students with the knowledge of current scientists. In order to learn the amount of scientific processes taught in school, students need to develop techniques to be able to pursue goals persistently, to use their existing knowledge for solving problems, to determine goals autonomously and to monitor their learning processes. Scientific inquiry learning is accepted in the domain of complex science as an approach to design activities that bring students closer to science (de Jong & Joolingen van, 1998; Dunbar, 1993; White, 1993). Innovations in educational technology can help to improve inquiry activities in schools. According to Chinn & Hmelo-Silver (2002), recently developed activities by researchers can support the goal of enriching scientific inquiry activities. Their study shows that scientific content illustrated in schoolbooks rather gives the learner the impression of science being a list of facts. Four hundred and sixty-eight activities in nine middle school and upper elementary school books were analyzed using a coding scheme containing cognitive processes. The data was compared with an analysis of inquiry activities developed by researchers using the same cognitive categories. The results indicate a big gap between the researcher-developed tasks and the textbook tasks concerning the requirement to engage in reasoning tasks. For example, Chinn and Malhotra (2002) report a big difference in encouraging students to recognize and develop simple controls autonomously vs. choosing them from a provided, limited set. A similar difference is found in the implementation of multiple scientific inquiry cycles using the same method to gain evidence about one specific phenomenon. Especially with respect to inquiry processes, textbooks seem very weak. Chinn and Malhotra (2002) could not find any textbooks that encouraged students to engage in common inquiry processes such as generating hypotheses by themselves, transforming observational knowledge into data, graphing results and variables relevant to the research question. Current developments in computer-based inquiry environments aim at overcoming this lack of involvement (Joolingen van, de Jong, Lazonder, Savelsbergh, & Manlove, 2005; Linn & Slotta, 2000; White et al., 2002).

2.2 Inquiry Learning

Inquiry learning shares aspects with other approaches such as discovery learning and problem solving. The following chapter will present a definition of inquiry learning and contrast it to related approaches to learning. Subsequently prominent approaches to inquiry learning are described.

Definition of Inquiry Learning

Inquiry learning activities have been confirmed to be effective for learning science (Chinn & Malhotra, 2002; Hmelo-Silver et al., 2007). They help students to develop understanding of how scientists study the natural world (National Research Council, 1996).

Inquiry. The National Research Council defines inquiry as follows: “Inquiry is a multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations.” (National Research Council, 1996, p. 23)

Inquiry Learning. Learning in the context of inquiry takes place when new experiences lead to a lasting change of the theories that exist in the learner’s mind. These experiences may be based on new experiment data or other kinds of evidence. The process of coordinating new evidence with existing understanding becomes visible through explanations, which represent the scientific reasoning process that learners undergo.

Similar Approaches to Learning

Traditional Classroom Learning. Inquiry learning is different from traditional school learning in one important aspect. It does not try to reduce the learning content to relevant information that can be acquired. It rather aims at putting the focus on methods and processes that help the learner to explore a problem space. These methods and processes are adapted from what scientists do when investigating science. New advancements in computer-based learning are beneficial for inquiry learning because students can use instruments of scientists such as modeling environments, simulations, and data plotters. Technological tools provide a wider access to richer and more scientifically grounded experience than traditional textbooks and lab experiments (Bransford, Brown, & Cocking, 1999). Furthermore, the exploration of science in technological advanced settings is supporting students’ natural curiosity because scientific phenomena can be simulated and embedded in rich contexts. Students can utilize computer-based environments to adjust the level of complexity in the same way scientists do. For example, students can run controlled experiments by changing one variable at a time and thus explore a phenomenon step-by-step. This engages students in a cycle of formulating conclusions and running into new problems, which results in a new question.

Problem Solving. Inquiry learning shares many aspects with problem solving. Inquiry activities are similar to problem solving activities, because just like problem solving, inquiry involves thinking that is directed towards achieving a specific goal. The specific goal in scientific inquiry lies in investigating a question or hypothesis that is determined before running an experiment in order to find answers to this question or hypothesis. Newell and Simon (1972) defined problem solving as a process of transformation using operators from an initial problem state to a goal state. In terms of this definition of problem solving, the initial state in inquiry learning is the development of a hypothesis; the goal state is the rejection or acceptance of that hypothesis. The operators are processes and methods, leading from the initial hypothesis to the final phase of an experiment. Similar to problem solving, inquiry learning can be regarded as a challenging domain, because it requires regulation to solve problems (Sandoval & Reiser, 2004).

Discovery Learning. De Jong (2006) defines inquiry learning as guided discovery learning. Although discovery learning itself puts the learner in the role of a scientist, inquiry learning just mimics the process that scientists engage in. In contrast to discovery learning, advocates of inquiry learning agree that learners need to be guided to learn from running experiments (Hmelo-Silver et al., 2007). Discovery learning and inquiry learning share the mutual goal of emphasizing the active role of the learner. Students acquire knowledge through testing their own knowledge by coordinating new experiment results with existing knowledge. This coordination process can be enabled through specific inquiry activities such as autonomous hypothesis generation and creating situations of cognitive conflict (Limón, 2001).

Existing Approaches to Inquiry Learning

Prominent approaches to inquiry learning emanate from a two-level view that distinguishes between an object-level system and a meta-level system (Nelson & Narens, 1994). At an object-level, activities directly affecting performance (e.g. developing a hypothesis) are being carried out. Processes on a meta-level (e.g.

planning), enable a learner to guide performance at the object-level. At a meta-level, the learner engages in processes of regulation with respect to processes affecting performance. Although this two-level distinction is reflected in most approaches to inquiry learning, the descriptions and terminology differ within each category. De Jong and Njoo (1992) describe that processes in inquiry learning can be of *transformative* nature or of *regulative* nature (Figure 1). Processes encompassing transformation directly yield knowledge. These transformative processes take place at the object-level. In contrast, processes that have to do with regulation, emphasize the executive control aspect with regard to the learning process (Manlove, 2007; Njoo & de Jong, 1993). These regulative processes take place at a meta-level.

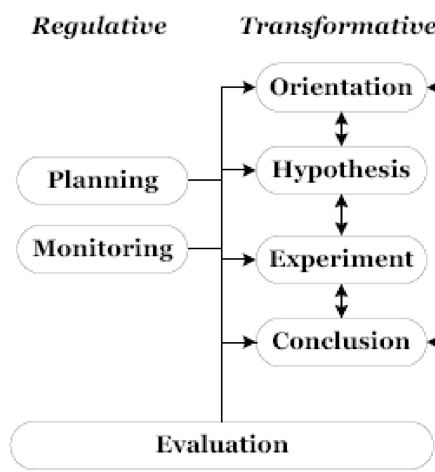

Figure 1. Processes of Inquiry (Manlove, 2007)

In accordance with de Jong and Njoo (1992), Kuhn and colleagues (Kuhn, Black, Keselman, & Kaplan, 2000) distinguish between processes at the object-level and processes at the meta-level. In contrast, Kuhn calls processes at an object-level *knowing strategies* and processes taking place on a meta-level she calls *meta-level functioning*. Knowing strategies refer (just like transformative processes*)* to domain-general activities that are applied to acquire new knowledge about a phenomenon. Processes of meta-level functioning (see left-hand side of Figure 2) are (just like regulative processes) necessary to execute valid knowing strategies.

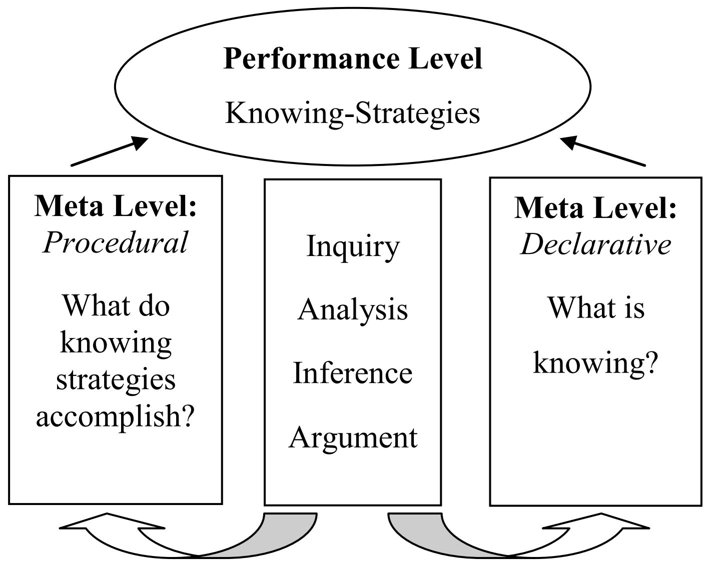

Figure 2. Processes of Inquiry (Adopted from Kuhn et al., 2000)

Both approaches by de Jong and Njoo (1993) and Kuhn (Kuhn et al., 2000) propose a two-level model, which consists of an object-level and a meta-level. Both knowing strategies (Kuhn et al., 2000) and transformative processes (Njoo & de Jong, 1993) refer to processes taking place at the object-level. They are applied to acquire knowledge during inquiry. These processes will be subsequently referred to as inquiry processes. The processes of meta-level functioning (Kuhn et al., 2000) and regulative processes (Njoo & de Jong, 1993) are described as processes taking place at a meta-level that are needed to regulate the execution of processes on the object-level. They will be subsequently referred to as regulation processes. In the theoretical framework of the present dissertation, the two-level view of object and meta-level is advanced (Figure 3). At the object-level, inquiry processes are of main importance. At the meta-level, a distinction is made between reflection and regulation processes. Reflection can be triggered through articulating explanations as described in Chapter 2.2.2. Engaging in regulation processes implies that reflection has taken place, but reflection does not necessarily presume the engagement in regulation processes. Both, reflection and regulation processes are assumed to affect the object-level positively. Particularly regulation processes are assumed being necessary to engage in scientific reasoning.

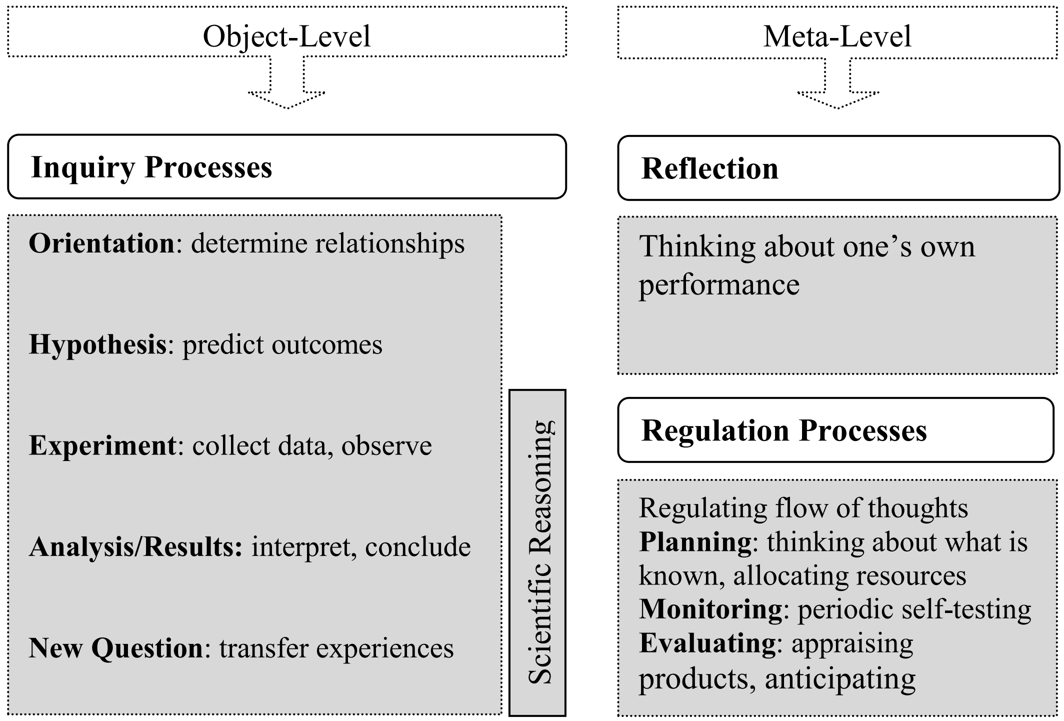

Figure 3. Processes During Inquiry Learning

The outline for the theoretical framework will be as follows: Processes taking place on the object-level, called inquiry processes, are described in the following chapter (2.2.1). Processes taking place on a meta-level (reflection and regulation processes) are described in the subsequent chapters (2.2.2 and 2.2.3). The distinction between three types of processes will be kept in the chapters elaborating *Problems in Inquiry Learning* (Chapter 2.3) and *Support During Inquiry Learning* (Chapter 2.4).

2.2.1 Inquiry Processes

Based on the approaches of inquiry learning described above, I will now focus on processes taking place on the object-level: *inquiry processes*. During inquiry learning, inquiry processes take place in respective inquiry phases.

Inquiry Cycle

Inquiry learning is often used as a method to guide the learner through complex scientific problems. It is an activity that involves several phases such as coming up with a research question and developing a hypothesis. In a next phase, the research question is investigated by systematically altering variables in an experiment (Künsting, Thillmann, Wirth, Fischer, & Leutner, 2008). Data from this experiment including several experiment runs and students' observations can then be used in an analysis and evaluation phase to build the base for developing scientific knowledge. Although the phase of collecting empirical data can vary depending on the approach taken (Quintana et al., 2004), much iteration is required (Blank, 2000; White & Frederiksen, 1998). Therefore, to engage students in scientific thinking by investigating particular problems, a continuous cycle of inquiry is needed (White & Frederiksen, 2000). Inquiry learning is cyclical; the investigation of a phenomenon requires usually more than conducting one experiment because results from one experiment often lead to conducting a follow-up experiment. After a first full inquiry cycle, spanning from orientation to analysis and results, there should be a next full inquiry cycle and so forth. An inquiry activity also can and should be iterative, because the inquiry cycle does not consist of a rigid sequence of phases, but of a flexible one, which can be adapted. That is why, the scientific method can help learners during the scientific investigation process. Every phase of the inquiry cycle leads to the next phase of that cycle. This sequential process allows the learner to transform empirical data into knowledge, and this knowledge leads to a new question, which then can be investigated in the next inquiry cycle.

Inquiry Phases

The phases in an inquiry cycle are important for a learner in order to process the information he or she generates when running an experiment. Typically, inquiry cycles that are mentioned in inquiry research consist of the following phases: orientation phase, hypothesis phase, experiment phase and analysis/results phase (Löhner, Joolingen, Savelsbergh, & Van Hout-Wolters, 2005). Even though most advocates of inquiry learning promote the cyclical nature of inquiry, the cycle is often not explicitly represented in the inquiry phases (e.g., by adding a particular phase) but suggested through the visualization of a cycle (White & Frederiksen, 1998). In order to make a transition from one to the next cycle explicit, a phase called *new question* seems useful. Subsequently, all phases will be described in detail starting with orientation phase and ending with new question phase.

Orientation Phase. Orientation is the first phase of an inquiry cycle, in which the learner develops global ideas about the phenomenon of investigation (de Jong, 2006). The orientation phase is a crucial step in the inquiry cycle, because it prepares the learner to develop a research question. If learners investigate a phenomenon, they need to have a rough understanding about the variables that build the construct of investigation and its relationships. For example, in Biology we know that the photosynthetic process is responsible for plant growth, which leads to biomass production. Aspects such as light intensity, nutrients etc. have influence on biomass production to various degrees. Although scientific experiments can provide answers to what extent a variable affects another, the learner usually holds a general understanding of the variables that may play an important role in the process. For example, students usually know that plant growth is dependent on sunlight but they do not know the extent of this dependency (in relationship to other variables like water). The orientation phase allows the learner to explore his or her understanding, to become aware of one's own understanding and to identify aspects, which are unknown. De Jong and colleagues (de Jong et al., 2002) called these ideas, which develop during the orientation phase, *issues*. The ideas are not as concrete as a hypothesis, but they form the basis for the subsequent experimentation process. An orientation phase during inquiry varies with regard to depth and approach taken. During the exploration of a problem space students need to identify and determine variables that are important in the context of the phenomenon. The goal of the orientation phase is to narrow down to the variables that will define the experiment to be conducted. For example, in a study conducted by Wu and Hsie (2006), students identified variables that affect a runner's speed and causal relationships between variables. The finale of the orientation phase is a research question that specifies the dependent and independent variables of the experiment to be conducted in this cycle.

Hypothesis Phase. The hypothesis phase allows the learner to predict outcomes and justify their prediction. Although the prediction includes specified values of variables and outcomes, the hypothesis can involve broader, more theoretical variables, which are specified describing ranges of values (de Jong, 2006). In an inquiry cycle, a learner develops a hypothesis at a point at which not all variables and relationships of a phenomenon are known. A learner formulates assumptions about a relation between two or more variables and the conditions in which this experiment shall be tested. Assumptions include not only a specification of relevant variables. They also involve justifications, which take into account related principles of the phenomenon to be investigated.

Experiment Phase. In the experiment phase, students collect data to answer the previously stated hypothesis. Prior to data collection, a learner must design an experiment with regard to the variables that have been specified in the hypothesis. The testing itself involves changing variables within one or several experiment runs to measure effects on the dependent variable. Students should enrich the collected data with a description that elaborates the data results. This description should not yet include interpretation of data.

Analysis/Results Phase. In the results phase, students interpret the collected data in relation to the hypothesis stated earlier in the inquiry process. This interpretation involves a comparison of the prediction made during the hypothesis phase with the experiment data and a description of a possible gap between hypothesis and experiment data. In addition, the learner needs to generalize the results and describe implications in the broader context of the phenomenon (de Jong & Njoo, 1992).

New Question Phase. Developing a new question is an activity that transfers experiences from the past experiment(s) to the next experiment. This new question is part of the broader investigation goal of an inquiry cycle. Therefore, new insights are reflected in the new question.

Summary. In inquiry learning, learners engage in a cycle of inquiry, which includes an orientation phase, a hypothesis phase, an experiment phase and an analysis/results phase and a new question phase. Within these phases, learners need to come up with a question, develop a hypothesis, and conduct an experiment by systematically controlling variables. Data from the experiment are used as evidence to draw conclusions, and newly gained insights are used to develop the new question.

2.2.2 Explanations

A central component of inquiry learning is the articulation of explanations. On the object-level, learners develop explanations as part of the inquiry processes within an inquiry cycle. Explanations have been defined in various ways. Still, there seems to be a mutual understanding among researchers that explanations go beyond the phenomenon that is being observed. Hence, an explanation is more than a description or the activity of paraphrasing (Solomon, 1986). Solomon generally states that an explanation must involve the connection "between the event that is being explained with some other real or possible happening" (Solomon, 1986, p. 41). Brewer and colleagues (Brewer, Chinn, & Samarapungavan, 1998) argue that a statement has explanatory power only when a larger conceptual framework is provided that goes beyond the described phenomenon. In inquiry learning, an explanation involves relating experiment data and a learner's understanding with reference to the underlying principles. If the relation between a learner's understanding and empirical data is drawn hypothetically, the explanation includes *justifications* related to the hypothesis (Figure 4 on the left). These justification explanations are developed before running an experiment and collecting data. If the relation is developed by drawing evidence from observations (e.g., experiment data), the explanation includes *inferences* (Figure 4, on the right). Inferences are developed when data from experiments is available. When subjects develop justifications or inferences, they fill the gap between predicted data or observed data and their own current understanding. Filling this gap, for instance, is achieved through scientific reasoning (Scriven, 1988). Scientific reasoning requires making a causal link (Rips, 1998) between changes of one variable affecting the change of another. It is necessary for inquiry learners to engage in scientific reasoning to understand underlying principles. Scientific reasoning is a feature of a good explanation within the context of inquiry learning.

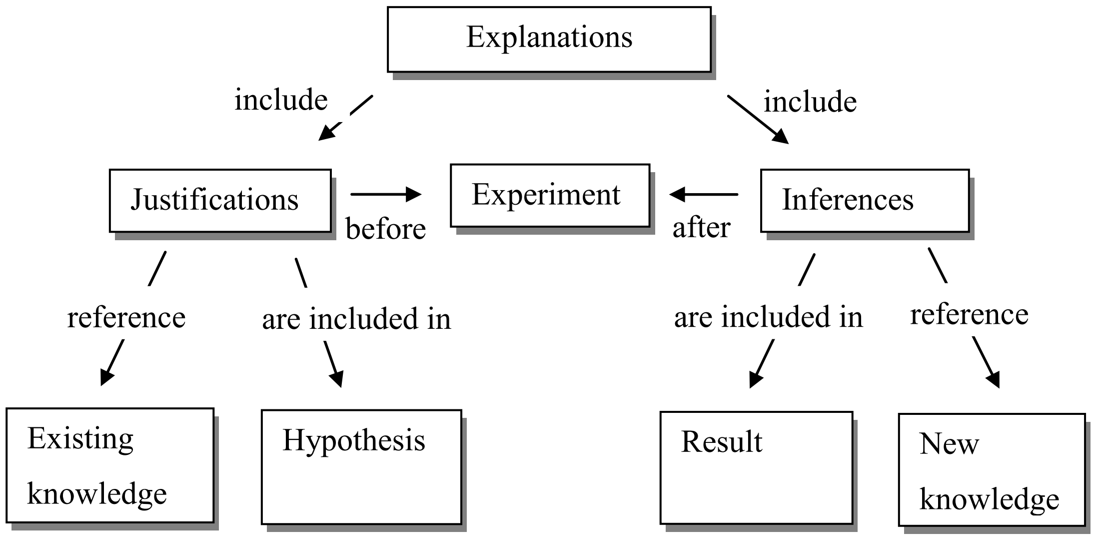

Figure 4. Justifications and Inferences

Types of Explanations in Inquiry

In inquiry learning, learners are expected to develop scientific explanations. When students develop explanations during inquiry learning, they often engage in everyday reasoning processes instead of scientific reasoning processes. Indeed, scientific explanations are similar to everyday explanations on many accounts. Both share that explanations provide a larger framework that goes beyond the original phenomenon and they provide a feeling of understanding (Brewer et al., 1998). Moreover, explanations can be *causal-mechanical* or *functional-intentional*. Causal-mechanical explanations describe a mechanism. They can provide an answer to a question that starts with “how”:e.g., “How is sugar being created during the photosynthetic process?”). Causal-mechanical explanations are provided to describe “how” something happens. In contrast, functional-intentional explanations describe not (only) a process but also presume some kind of purpose. Those explanations are provided to answer questions starting with “why”:e.g., “Why do plants turn towards the light?”). Hence, they have a teleological character, because they are based on the assumption that changes happen to serve a purpose, function, or goal. Functional-intentional explanations can result in anthropomorphic explanations and animistic explanations. Anthropomorphic and animistic explanations refer to goal-directed behavior that is drawn from human experience or from observing animal behavior (e.g., “Leaves turn their face towards the sun, because sun energy is the food for the plant.”). These explanations include terms such as “face” or “food”, which express an attribution of human-like behavior (Christidou & Hatzinikita, 2006). In science, researchers use causal-mechanical and functional-intentional explanations to describe phenomena. Both types of explanations exist in every day reasoning and are common for scientific explanations as well.

Besides these shared aspects, scientific explanations have also characteristics that are distinct from everyday explanations. Brewer and colleagues (Brewer et al., 1998) claim that scientific explanations must be testable, hence one can collect evidence (e.g. in form of data) to confirm or disconfirm the explanation. On the other hand, everyday explanations are often empirically verifiable. Therefore, testability can be seen as an additional requirement of scientific explanations but not as a feature that separates everyday explanations from scientific explanations.

Role of Explanations During Inquiry Learning

Explanations have been investigated in science as a product of learning and as a process component leading to that product. According to the first aspect, explanations are viewed as a product, which can inform about the learner’s knowledge state. According to the second aspect, research has seen writing explanations as a process, being beneficial during an inquiry cycle. While the first aspect will be examined in Chapter 2.4.2, I will focus now on the second aspect, viewing explaining as a process. Explaining is a beneficial process during inquiry learning because it offers means to engage in scientific reasoning.

Explaining as a Means to Engage in Scientific Reasoning

A deeper processing of newly acquired knowledge during an inquiry cycle can be achieved through scientific reasoning. Generating explanations is one way to engage in scientific reasoning.

Scientific reasoning is a broad research topic. Zimmerman (Zimmerman, 2000) identified two areas of research that approach the investigation of scientific reasoning quite differently. The first area of research requires the learner to apply their existing understanding to explain specific phenomena. It includes research of conceptual change. Children's naive beliefs are investigated in the attempt to find deviations from beliefs that are held by scientists (Vosniadou & Brewer, 1991). Researchers of conceptual change are interested in individuals' scientific reasoning to examine their understanding including synthetic mental models that individuals hold. In order to have insight into an individual's understanding, researchers need to pose questions that engage students in scientific reasoning. Usually research in the area of conceptual change does not require subjects to engage in inquiry activities (e.g. running experiments), but researchers elicit existing thinking processes (Zimmerman, 2000).

The second area of scientific reasoning research requires subjects to carry out activities. This dissertation focuses on the second area of scientific reasoning research involving learners in inquiry tasks. The most prominent approaches to scientific reasoning will be presented.

There have been several approaches to scientific reasoning in the area of inquiry learning. The Scientific Discovery as Dual Search Model (SDDS) by Klahr and Dunbar (1988) is a framework that sees scientific reasoning as an aspect of problem solving focusing on the integrated search in two problem spaces, with a third space that was addressed later. The problem spaces consist of the hypothesis space and the experiment space. The search in the hypothesis space is dependent on prior knowledge and/or observations from previous experiments. The search in the experimentation space however involves searching the domain and then developing an experiment that can test the hypothesis developed earlier. In the third space called evidence evaluation, learners decide whether the current hypothesis will be rejected, accepted, or modified. The coordination of all three space requires scientific reasoning and results in the development and revision of one's own understanding (Klahr, 2005).

Chinn and Brewers (2001) *models-of-data approach* advocates that learners develop a model in which theory and evidence are "intertwined in complex ways in models of data so that it is not always possible to say where one begins and the other ends" (Chinn & Brewer, 2001). They describe that scientific reasoning includes developing a cognitive model that contains both theory and data (similar to what Kuhn describes as evidence) and that these two components cannot be separated once they are integrated in a cognitive model.

In accordance to Chinn and Brewer (2001), Kuhn and colleagues focus on the coordination of theory and evidence (Kuhn, 1989; Kuhn & Pearsall, 1998; Kuhn, Schauble, & Garcia-Mila, 1992). They advocate that scientific reasoning is the coordination of existing theories with new evidence. With existing theories, Kuhn and Pearsall (1998) refer to the learner's existing knowledge. With evidence, the authors refer to data that has been collected during an experiment that aims to demonstrate the truth of an assertion. Evidence is used as a basis for developing inferences. Drawing inferences from data requires knowledge coordination. Knowledge coordination requires differentiating, integrating, and restructuring own knowledge (Davis & Linn, 2000). Kuhn asserts that these coordination processes are the "most central, essential, and general skills that define scientific thinking" (Kuhn, 1989, p. 674)

All three approaches presented above advocate scientific reasoning as a way to engage in deep processing. The SDDS model by Klahr and Dunbar (1988) emphasizes scientific reasoning before an experiment is run. The models-of-data approach by Chinn and Brewer as well as Kuhn's' approach focus on scientific reasoning after the experiment is run and data has been collected. All three approaches are relevant to describe the role of scientific reasoning in an inquiry cycle. When learners follow an inquiry cycle, they engage in scientific reasoning resulting in explanations during a hypothesis phase and an analysis/results phase. If the explanations are developed in the hypothesis phase, they are called justifications. If the explanations are developed in the analysis/results phase, they are called inferences.

Scientific reasoning plays an important role when investigating learner's explanations. Another important aspect is reflection.

Explaining as a Means to Engage in Reflection

Several researchers (Gauld, 1989; Sandoval, 2003; Toth, Suthers, & Lesgold, 2002; White & Frederiksen, 1998) suggest that students gain scientific understanding, when opportunities for reflection by developing explanations are provided. Explaining can trigger reflection, that is, to encourage ones thinking about thinking (Dewey, 1933). Reflecting happens on a meta-level (Chapter 2.2) and it can affect the performance on the object-level positively (Nelson & Narens, 1994). Explanations externalize thoughts and have therefore the potential to make thought processes salient that are usually covered (Scardamalia & Bereiter, 1985). From an information-processing point of view (Mayer, 2004), generating explanations based on the learning situation helps learners to develop new cognitive structures and to modify existing knowledge.

During problem solving, articulating explanations can help the learner to reflect on the learning process and hence to promote the success of solving a problem (Chi, Lewis, Reimann, & Glaser, 1989; Ferguson-Hessler & de Jong, 1990; Pirolli & Recker, 1994). Research in the context of problem solving has widely focused on the support of a specific type of explanation called self-explanations. According to Chi and Bassok (1989), the self-explanation effect describes the discovery that students learning with worked-out examples and taking the time to self-explain these examples, learn more. The original self-explanation effect refers to a study by Chi and colleagues (Chi et al., 1989) in which problem solvers had the possibility to self-explain and spontaneously did so or did not. Results showed that expert problem solvers were the ones who explained more, while poor problem solvers explained less. The self-explanation effect has been replicated in the area of problem solving. In a first attempt of defining this effect, Chi and VanLehn (1991) mentioned inferences to be the main activity that happens during self-explaining. In a second attempt (Chi, 2000), Chi added the revision of mental models besides making inferences. Chi's more current definition of the self-explanation effect includes the access of prior knowledge (Roy & Chi, 2005).

During inquiry learning, reflection is a crucial component. When students learn a scientific concept via the inquiry method, their initial understanding in form of a hypothesis is challenged through the experiment they are running and the data results they get. This conflict resulting from an inconsistency between hypothesis and data is robust, and students are tending to hold on to their hypotheses even when they are confronted with data results that contradict their hypotheses (de Jong & Joolingen van, 1998). Hence, it seems that students do not reflect enough to discover their conceptual deviance from the principles reflected in their experiment outcomes. Explanations in these situations can help to reflect on the conflicting data and lead to an adaptation of the learners' initial understanding.

Summary. Developing scientific explanations in inquiry learning involves scientific reasoning. Scientific explanations share aspects with everyday explanations, but they are also distinct in one important aspect: Scientific explanations need to be testable. In general, engaging in explanation building promotes reflection, which is considered to enhance scientific understanding. Explanations in inquiry learning are of a specific type, requiring the learner to engage in scientific reasoning. Scientific reasoning research presumes that a learner successfully coordinates existing knowledge with new evidence from experiments.

Reflection in general might be beneficial during inquiry learning, but it is questionable whether it is sufficient especially when engaging in scientific reasoning. Specific processes besides reflection might be necessary to engage in scientific reasoning successfully.

2.2.3 Regulation Processes

As described in Chapter 2.2, prominent approaches of inquiry learning distinguish between processes taking place at a meta-level and activities at an object-level. This distinction that has been suggested by Nelson and Narens (1994) is also advocated by many researchers in the area of metacognition (Brown, 1978; Flavell, 1979). With reference to the characterization by Nelson (1999), metacognition is viewed as the interplay between the meta-level and the object-level. From an information-processing point of view, metacognition involves top-down processes that regulate the information processing on the object-level. Metacognition has been predominantly seen as a two-component concept, comprising of knowledge of cognition (declarative aspect) and regulation processes (procedural aspect) (Brown, 1987; Flavell, 1987; Schraw & Moshman, 1995). There is a wide agreement on the two-component approach (exceptions are e.g., Pintrich, Wolters, & Baxter, 2000), but representatives of metacognition research have been less systematic when it comes to elaborating processes within both components. Terminology and components of the main approaches to metacognition will be presented subsequently.

Flavell (1987) sees *metacognitive knowledge* and *metacognitive experiences* as the two key components of metacognition. Metacognitive knowledge refers to acquired knowledge about cognitive processes. He further divides metacognitive knowledge into knowledge about person variables, task variables and strategy variables. Knowledge about person variables includes knowledge about how one learns and processes information. Knowledge about task variables refers to knowledge about the nature of the task and its specific demands and constraints that go along with it. Knowledge about strategy variables refers to knowledge about both cognitive and metacognitive strategies. Cognitive strategies are directed towards the activity itself and metacognitive strategies are used to monitor the effectiveness of cognitive strategies. In sum, Flavell argues that the more metacognitive knowledge a learner has, the better he or she regulates cognition. Flavell calls the second component, besides metacognitive knowledge, metacognitive experience. Flavell (1979) claims that metacognitive experiences can activate metacognitive and cognitive strategies. Metacognitive strategies are distinct from cognitive strategies to the extent that cognitive strategies are “invoked to make cognitive progress and metacognitive strategies to monitor” this progress (Flavell, 1979, p. 909). For instance, if a student realizes that he or she doesn’t understand the effects of the variables in an experiment he or she wants to conduct (metacognitive experience), he or she thinks about what may be the best strategy to acquire that knowledge (metacognitive strategy), e.g., re-reading the relevant chapters in a book (cognitive strategy).

Brown (1987) views metacognition as knowledge of the cognitive system and control of the cognitive system. Knowledge of the cognitive system refers to the individual’s knowledge of one’s own cognitive processes. Although Brown includes this distinction between knowledge and control in her research, her work has been focusing merely on the control part of metacognition, which she refers to as *metacognitive skills*. According to Brown, metacognitive skills involve the engagement in processes by which individuals control their own thinking. These control processes are of executive nature and include planning, checking, monitoring, and prediction. All these processes contribute to processes on the object-level.

Similar to Brown, Kluwe (1987) emphasizes the executive processes in his research. He distinguishes between declarative and procedural knowledge, in which the procedural knowledge part is directed towards the controlling of one’s own cognitive activities. Kluwe calls his executive processes *executive decisions*, which include four executive activities: classification, checking, evaluation, and anticipation.

Schraw and Moshmann (1995) divide metacognition in *knowledge of cognition and regulation of cognition*. Knowledge of cognition includes declarative, procedural, and conditional knowledge. Declarative knowledge is similar to Flavell’s knowledge about person variables. Procedural knowledge is similar to

Flavell’s knowledge about strategies. Schraw and Moshmann (1995) and others (Desoete, Roeyers, & de Clercq, 2004) are distinct in their view of knowledge of cognition by explicitly including conditional knowledge (knowledge about what to do when). This is distinct to others like Flavell, Brown and Kluwe (Brown, 1987; Flavell, 1987; Kluwe, 1987) who have implied conditional knowledge by subsuming it under procedural aspects (Veenman, 2005). Regulation of cognition refers to “a set of activities that help students control their learning” (Schraw, 1998, p. 4) These regulation processes include planning, monitoring and evaluation. Planning refers to allocating recourses that affect performance. Monitoring refers to “one’s on-line awareness of comprehension and task performance” (Schraw, 1998, p. 5). Evaluation involves appraising products and efficiency of one’s learning. The regulation processes defined by Schraw are very similar to the processes described as metacognitive skills by Brown (1987) and as executive decisions by Kluwe (1987).

Table 1. Two-Component Approaches Related to Metacognition

	Knowledge of Cognition	**Regulation Processes**
Flavell (1987, 1979)	Metacognitive Knowledge	Metacognitive Experience / Metacognitive Strategies
Brown (1987)	Knowledge of the Cognitive System	Metacognitive Skills
Kluwe (1987)	Declarative Knowledge	Executive Decisions
Schraw & Moshmann (1995)	Knowledge of Cognition	Regulation of Cognition

Metacognition research that has its roots in information processing theory (e.g., Brown, 1987; Kluwe, 1987; Schraw & Moshman, 1995) emphasizes the executive control aspect (Klauer & Leutner, 2007). Metacognitive knowledge alone does not lead to an appropriate execution of available processes (Veenman, Kok, & Blöte, 2005). For example, a learner may know that re-testing the learning process by anticipating outcomes and alternatives is important during an inquiry; however, he or she still might not do it. Therefore, this line of research sees the focus of metacognition on the regulation of cognition and its executive role in information processing (Klauer & Leutner, 2007). Processes within regulation of cognition have been labeled differently by various researchers (Table 1). Subsequently, processes involving regulation of cognition will be referred to as *regulation processes*.

Types of Regulation Processes in Inquiry Learning

Regulation processes have been recognized as an important aspect of successful inquiry learning (Njoo & de Jong, 1993). During inquiry learning, students need to engage in regulation processes to take on scientific reasoning. Regulation, being the executive control part of metacognition, comprises of *planning, monitoring,* and *evaluating* (Brown, 1987; Schraw & Moshman, 1995).

Planning involves thinking about what is known and what is not known (Brown, 1987) in relevance to the upcoming inquiry. It includes systematically exploring the problem space and developing a strategic plan to successfully design and run an experiment. Particularly, it includes planning next learning steps and allocating resources to outline those steps. Planning aims at optimizing performance for example by allocating time or attention for future actions (Flavell, 1987).

Monitoring involves checking the status and progress during the inquiry. It includes periodic self-testing of one's own understanding. Learners engage in monitoring through judging applied procedures (Lin & Lehman, 1999) and periodic self-testing to become aware of possible cognitive conflicts. They do so by prioritizing tasks and keeping track of possible mistakes (Kluwe, 1987; Schraw, 1998). Monitoring aims at raising awareness of one’s own understanding and task performance (Schraw & Moshman, 1995).

Evaluation involves appraising products (Schraw, 1998) by, for example, re-evaluating one's plans and conclusions, adapting regulation processes and plans for the next task. Evaluation can lead to generating a new working plan by implementing systematic steps in an activity and also adapting these steps accordingly (Artelt, 2000). The category evaluation consists of evaluation-of-self and anticipated thinking. Evaluation-of-self refers to reactively judging one's own decisions (i.e., "I was completely on the wrong track"), which also can include judgments about specific methods used during inquiry (for example the type of simulation used or the type of experiment chosen). *Anticipated thinking* can be considered as a self-testing process, because through alternative anticipation, students test and extend their own knowledge. Anticipated thinking can be described as proactive behavior that goes beyond the problem space that is considered for the ongoing inquiry. This behavior is proactive, because the learner anticipates alternative and new events leading to a progress of understanding underlying principles. It also requires forethought towards the next experiment to be conducted. According to Zimmerman (2004), proactive behavior is beneficial and has considerable advantages in comparison to reactive behavior. Proactive behavior enables learners to direct their learning towards new and relevant goals, while reactive learners focus only on the event at hand. In inquiry learning, a student who is able to anticipate distinct future experiments or additional relevant variables has advantage over a student showing only reactive regulation behavior. Reactive regulation behavior may involve the evaluation of experiment results without considering further implications. Anticipated thinking has been subsumed under evaluation and has not been treated as a fourth distinct category of regulation (see also: Kluwe, 1987), because anticipation is seen as a process that is highly intertwined with evaluation of self.

Regulation Within the Respective Phases of Inquiry

When students formulate explanations, specific regulation processes need to take place to be able to employ explanations effectively. For example, a learner who actively regulates his or her own thinking during an inquiry cycle, iteratively asks questions such as “What do I know about this variable?”, “How are my results different from my hypothesis?” or “Do my conclusions make sense?”.

In every phase of an inquiry cycle, specific aspects of regulation are expected to be beneficial. In the orientation phase, planning takes place when learners have the opportunity to explore a problem space by thinking about what is known and what is not known. Particularly, this includes the activation of prior knowledge and the utilization of prior experiences (e.g. from prior experiments) in relation to the problem space. Through activation of prior knowledge, the learner should limit the problem space by identifying variables, which are relevant and irrelevant. During the hypothesis phase, planning is necessary to specify next experimentation steps including setting up the experiment design. This planning involves utilizing existing knowledge. Monitoring is important for maintaining the plan of the experimental design. During the experiment phase, learners engage in periodic self-testing and keeping track of mistakes by monitoring the data collection process. During the results phase, learners engage in evaluation by appraising their findings. During the new question phase, learners may direct their thoughts on formulating new predictions, which will manifest themselves in the next inquiry cycle.

Regulation processes stated above are highly interdependent (Veenman, 2005), in the sense that they may affect each other positively and negatively. When a learner takes time to allocate resources for planning and to think of how to design an experiment optimally before running it, this may lead to advantages during the hypothesis and experiment phase, because the learner may be able to rely on a plan, which helps to keep track of mistakes and keep track of progress made. During the results phase, the learner may easily appraise products and his or her own learning process by benefitting from tracking own mistakes made earlier in the inquiry cycle. A successful evaluation may lead to considerations of adapting the learning process for the next cycle.

Role of Regulation in Inquiry Learning

In general, regulation processes are assumed to be contributing to improve performance on the object-level (Kluwe, 1987; Schraw, 1998). Research indicates that engaging in regulation leads to a deeper processing of the principles to be learned and to a higher level of understanding and learning (Bransford et al., 1999). Regulation is needed in all domains of learning (Veenman & Verheij, 2003), but regulation requirements differ depending on the nature of learning settings. For example, regulation is needed while learning from a science text as well as while learning from running scientific experiments in an inquiry learning setting (Leutner & Leopold, 2006; Wirth & Leutner, 2006). However, on closer inspection, regulation related to inquiry tasks places very specific demands on the learner that differ from learning from text. During learning from text, the relevant information is presented to the learner, and regulation deals primarily with selecting, organizing, and integrating that information (Leutner & Leopold, 2006). During inquiry learning, however, the relevant information is usually not presented to the learner. Instead, the learner has to generate the information to be learned by him or herself in terms of gaining evidence from conducting experiments (Wirth & Leutner, 2006). Thus, in inquiry learning, specific regulation processes are needed because of its open-ended nature. Often, the learning path is not pre-defined, which requires learners to grasp processes that require systematic thinking. Especially for the types of problems that students investigate in an inquiry cycle, rudimentary problem solving approaches such as trial and error will not be sufficient. In inquiry learning, tasks often have to do with optimization. Regulation processes can facilitate approaching these optimization tasks systematically, in order to keep track on the learning process and in order to manage the evaluation of the learning process. Planning helps a learner to estimate time for a given task by developing a relevance hierarchy. Monitoring can be used as a supportive process to maintain a plan. For example taking time to monitor one’s made and upcoming actions helps to avoid becoming stagnant within task and to make decisions about whether ideas should be rejected or tested (Schoenfeld, 1987). Evaluation processes are specifically important during complex inquiry activities because they assure that newly gained knowledge will be tested, re-evaluated, and applied in new situations. For instance, the ability to anticipate new experiments is necessary to develop hypotheses autonomously in open-ended inquiry situations.

Role of Regulation for Scientific Reasoning. According to Kuhn (2001) and others (Moshman, 1999), regulation processes (metastrategic functioning in Kuhn's terms) might be an important moderating variable affecting scientific reasoning. Kuhn (2001) claims that an important factor to become a scientific reasoner is to regulate the execution of appropriate processes. Scientific reasoning is a demanding activity because it requires coordinating existing knowledge successfully with newly gained evidence from experiments. This coordination is bi-directional. New evidence affects the way learners evaluate not only their own understanding, but also learners' own understanding affects the way they conduct a scientific experiment. The success of this coordination is dependent on the degree of control that is attained during the coordination (Kuhn et al., 1992).

Summary. For successful coordination of one's own understanding with newly gained evidence from experiments, learners need to regulate their learning. Regulation consists of processes that guide the performance during inquiry activities. Specifically, regulation processes are necessary to engage in scientific reasoning.

2.3 Problems in Inquiry Learning

Many problems for learners arise when they are dealing with highly sophisticated inquiry tasks that require them to be equipped with expert inquiry expertise. Learners face specific problems that vary depending on their own understanding and the environment that they engage in. In contrast to scientists, learners lack knowledge about relevant actions during inquiry, autonomous reflection, and regulating one's own flow of thought. In the following, problems between inquiry phases and problems within inquiry phases will be described.

2.3.1 Problems During Inquiry Learning

Problems Between Inquiry Phases

Following the process of inquiry poses quite a challenge for inexperienced learners. For young learners, the most beneficial sequence of solving a problem or tackling a task is often not the one they choose to pursue. In the case of inquiry learning, the scientific method foresees a sequence, which is cyclical and iterative in nature (Chapter 2.2). Novice students often do not know how to adapt their inquiry cycle because they do not know which action is most relevant (Quintana et al., 2004). That is the reason why they do not choose the most beneficial actions. For instance, if a learner realizes that the results will not provide an answer to the question that was asked beforehand while determining the conditions of an experiment, the learner should consider going back to adapt the conditions for the experiment and possibly changing the hypothesis towards a testable one. Although most students in secondary school know the phases of inquiry, they often do not follow or adapt them to increase the chance of gaining accurate findings.

Besides a lack of knowledge about which step to take next, learners also have problems dealing with the complexity of an investigation (Quintana et al., 2004). For a novice, an inquiry activity is mentally more demanding than for an expert. This leads to a superficial analysis or complete skipping of essential processes. For example, inexperienced learners tend to skip essential phases like orientation or hypothesis and advance straight to running an experiment. The analysis of the problem space *before* conducting the experiment is an important factor that affects learning performance. Because learners often don’t analyze the problem space very deeply, they tend to act immediately (Veenman, Elshout, & Meijer, 1997) but not systematically. They may also get stuck in less relevant management tasks and hence fail to pursue the inquiry process (Quintana et al., 2004).

In sum, to support learners to cope with problems of following the inquiry cycle effectively, an explicit activity structure is needed which at the same time can be flexibly adapted.

Problems Within Inquiry Phases

Orientation Phase. Coming up with a testable research question is known to be one of the hardest steps during an investigation (Klahr & Dunbar, 1988). Inexperienced students have too broad and too complex questions in mind, which are often not testable with the experimentation tools available. Learners have difficulties to explore the problem space systematically. The goal of identifying relevant variables to formulate a research question requires the learner to determine aspects of the phenomenon that are not known yet. Learners have great difficulties to become aware of what they know or what they don't know about a specific problem or phenomenon. Therefore, appropriate tools need to be provided to support the learner in exploring the problem space systematically.

Hypothesis Phase. Even university students have problems to formulate a hypothesis that is syntactically correct (Njoo & de Jong, 1993). Often students do not know of which elements a valid hypothesis consists. Moreover, students are resistant to change their initially stated hypotheses. Dunbar (1993) defined this problem as the *unable-to-think-of-an-alternative-hypothesis* phenomenon.

Experiment Phase. Students have problems with setting up an experiment if too many aspects are not yet specified. Thus, students cannot specify the experiment to accurately test their earlier generated hypothesis (de Jong & Joolingen van, 1998). A common mistake of inexperienced students is not to isolate one parameter to be tested. Rather, students tend to alter more than one variable during experiments. As a result, students cannot use experiment data to answer their earlier stated hypothesis. Van Joolingen & De Jong (1991b) reported that students altered parameters that were independent from the research question stated earlier. Thus, students could not analyze the experiment data meaningfully.

Analysis/Results Phase. Another problem surfaces when interpreting data: Apparently, students tend to interpret data in a way that it supports the current hypothesis. This phenomenon, called *confirmation bias*, was investigated by Chinn and Brewer (2001). It describes that even if experiment data are pointing towards a disconfirmation of the hypothesis, students will draw conclusions from it that will confirm their initial hypothesis. Another issue has to do with the learner's goal definition. Pursuing the goal of answering a question and running an experiment often does not result in pursuing the more general goal of understanding scientific principles. Students often have problems to coordinate their new findings with their initial knowledge prior the experiment.

New Question Phase. Formulating a new question is a demanding task for a student. Students often fail to articulate an appropriate question, because the question is not related to pursuing a broader investigation goal (e.g., from a more general perspective of science education, Fischer et al., 2005; Klahr & Dunbar, 1988). Another problem is related to the testability of the questions. Students often formulate questions that are not testable with the equipment available.

Summary. Students in secondary school have often some idea of which phases an inquiry method consists of. However, it is challenging to adapt this method effectively. As a result, students often skip relevant phases or focus on aspects, which are not relevant for the learning process. In addition, students have various problems that they encounter within the phases of inquiry.

2.3.2 Problems of Developing Explanations

Even if inquiry support is offered, learners often miss out on opportunities to reflect on their deliberate approach to inquiry as well as on the content itself (White & Frederiksen, 2000). Reflection is necessary because students develop their own ideas during an inquiry cycle, but often these ideas are contradictory. Making ideas explicit through external representation makes it easier for students to discover inconsistencies in their beliefs (Chinn & Brewer, 2001). If students are not encouraged to justify decision steps along the inquiry process, they tend to simply work up the phases of inquiry without gaining understanding of the phenomenon being investigated (Kuhn & Pease, 2008). As a result, students will not adapt their inquiry process to their own needs. For example, they fail to discover mistakes soon enough in order to repeat experiment runs or to adjust the experiment design. Learners who are not reminded to make purposeful decisions might gain correct data results in an experiment but have no means to coordinate gained data results with existing knowledge; hence, they are not able to develop high quality explanations. There is a tendency that learners rather focus on the product than on scientific reasoning about the findings they just made (Reiser, 2004). The traditional inquiry cycle might even facilitate this product focus. A learner who does not devote time in articulating thoughts and decisions during an investigation will miss opportunities to coordinate knowledge actively.

Problems Concerning the Generation of Explanations

Learners have problems to generate explanations from scratch. When students develop explanations before running their experiments, students generally have difficulties to articulate and justify hypotheses (McNeill & Krajcik, 2008). Often students don't write explanations at all and just state a prediction without justifying it. As reported in the inquiry Chapter 2.3.1, students have often difficulties of giving up their initial hypotheses even in presence of contradicting data. Learners fail to distinguish between their own theories (e.g. justifications) and data that are either provided or gathered (Kuhn, 1993). Students have problems, e.g., during the hypothesis phase to provide justifications for their predictions. It seems to be a challenge for learners to transfer gained knowledge to explanations. Toth and colleagues (Toth, Klahr, & Chen, 2000) found that half of the students who were able to conduct scientific experiments failed in providing written justifications for their actions.

After an experiment is run, students often have problems to develop inferences. The inquiry method suggests that after running an experiment, observations should be made during the data collection phase. Students might be able to complete this task by explaining the results on a descriptive level, but they fail to infer from the data they collected. Students are not automatically prepared to explain observations by relating to underlying principles. They are stuck with writing up descriptions of what they observed. One reason might be the nature of inquiry itself: During the process of making inferences, they are left alone as the common inquiry method provides no structure to support developing inferences (Smith & Reiser, 2005). In sum, students have problems to generate explanations that serve as justifications or inferences during the inquiry cycle.

Problems Concerning the Quality of Explanations

As described above, generating explanations during an inquiry cycle poses a challenge for inexperienced learners. Even if learners are able to generate explanations, they still have problems to develop explanations of high quality. Explanations of high quality during inquiry learning include justifications (before the experiment has been run) and inferences (after the experiment has been run and data has been collected). Learners have problems concerning developing justifications. If learners predict outcomes of their experiment runs, they often do this without justifying their predictions at all, or they provide superficial justifications. Instead of backing up claims by referencing findings from previous experiments or existing knowledge about scientific principles, learners tend to provide superficial justifications, including statements such as “It is just the way it is”. Davis and Linn (2000) referred to this as “*no problem behavior*”. Learners also have problems concerning developing inferences. The pre-condition of developing an inference is to relate to experimental data. One problem is that students fail to reference their experimental data and therefore are not able to develop inferences properly (Sandoval & Reiser, 2004). If learners are able to relate to experimental data, they often do not do it properly, which leads to inferring problems. Kuhn and colleagues (Kuhn et al., 1992) refer to problems of inferring from experiment data as inferential error. The authors distinguish between inclusion and exclusion errors while developing inferences. False inclusion (e.g. “The more CO_2, the more photosynthesis will take place”) is based on a false causal implication from the cooccurrence of the cause and outcome. False exclusion (e.g. “CO_2 makes no difference, because it didn’t matter whether plants received 5000 ppm or 10000 ppm”) refers to a false implication from the absence of a causal relation. Students ,and people in general, lean towards producing inclusions instead of exclusions, because the presence of a relation is more salient than the absence of a relation.

Scientific vs. Everyday Explanations. Developing explanations during a scientific investigation poses a different challenge to the learner than developing explanations in everyday situations. In everyday situations, people are quite good at explaining changes that happen in the world. Often, these changes are related to behavior of people. To explain these changes in behavior, one can assume that people have a certain goal or belief (Ohlsson, 1992), which leads to that change. During scientific investigations, learners often tend to do the same. However, in science, the changes are mostly related to objects (Ohlsson, 1992). As a result, young learners attribute goals to objects in order to explain a change. This leads to the development of functional-intentional (see also Chapter 2.2.2) explanations in science (Tamir & Zohar, 1991), which don’t represent underlying mechanisms of a scientific phenomenon but purposes. Specifically in the domain of Biology, students lean towards formulating functional-intentional explanations, because these are more satisfying than causal-mechanistic ones. Abrams and colleagues (Abrams, Southerland, & Cummins, 2001) found for example, that young students were puzzled and confused if they were asked “how” a change occurred (instead of “why”). Thirty-one percent answered with an answer to a “why” question and another eleven percent could not answer at all. In comparison, more experienced students were more capable of answering “how” questions appropriately by providing a ”how” answer. In sum, developing explanations during inquiry learning poses more challenges to a learner than developing everyday explanations.

Summary. A learner who does not devote time in articulating thoughts and decisions during an investigation will miss opportunities to coordinate knowledge actively. In addition, the development of scientific explanations poses potential problems to a learner in comparison to everyday explanations. Specific problems occur within the phases of an inquiry cycle, which several authors trace back to the non-presence of a structure within the common inquiry method that appears to support the development of inferences.

2.3.3 Problems of Regulation

Kuhn (1993) claims that the capacity of students thinking about their own thought has a major influence on their scientific reasoning performance To succeed in scientific reasoning, students need to engage in the coordination of their own hypotheses and ideas with new data in a conscious and controlled way. Therefore, she argues that research should give more attention to ways of supporting students in regulating their own thoughts during scientific reasoning.

In science, learning the regulation of the learning process is important, because science is a complex and often, abstract domain. Especially when the learning path is not presented by the teacher, it is likely that students loose track and don't engage sufficiently in regulation processes.

Problems to Engage in Regulation

Students have problems to engage in regulation processes during inquiry learning (de Jong & Njoo, 1992; Manlove, Lazonder, & de Jong, 2007). Either they barely regulate at all or the regulation processes they use are ineffective.

Planning Problems. Inexperienced learners have problems to plan effectively. More experienced learners engage more in global planning as opposed to local planning (Bereiter & Scardamalia, 1987). They have more knowledge about when (i.e., before and not during a task) it is best to engage in planning processes (Schraw & Moshman, 1995). Njoo and de Jong (1993), for instance, investigated university students' engagement (besides other processes) in regulation processes. Students worked in pairs with a simulation tool for scientific engineering, specifically control theory. They received questions and problems as an assignment which they were asked to solve. Think aloud protocols showed that students indeed engaged in planning processes but processes were ineffective. Planning processes were found but plans were short time only. Students did not develop a systematic plan that helped them to structure their workflow.

Monitoring Problems. In the same study by Njoo and de Jong (1993), students did engage in monitoring, but monitoring processes were superficial. Superficial monitoring resulted solely in re-reading the assignment. Quintana and colleagues (Quintana, Zhang, & Krajcik, 2005) identified issues with poor time allocation between search tasks and other activities as one of the major problems during inquiry. Learners, who have problems to execute appropriate processes at the right time, fail to allocate time effectively. Lin and Lehman (1998) found that students having problems with monitoring tended to unsystematically switch back and forth while testing different variables. When these students discovered mistakes, they tended to start all over instead of starting where the error occurred.

Evaluation Problems. Inexperienced learners have problems to diagnose problems, which leads to an inability to correct problems (Bereiter & Scardamalia, 1987). Veenman and colleagues (Veenman et al., 2005) showed that young learners have problems to evaluate their answers and barely relate current to earlier problems.

Why do learners engage in regulation processes insufficiently? Based on Flavell's (1977) description of a production deficiency, Veenman and colleagues (Veenman et al., 2005) distinguish two reasons to explain the absence of regulation processes: production deficiency and availability deficiency. Production deficiency attributes absence of regulation processes to an inability to employ available regulation processes. Availability deficiency precedes that the learner hasn't any pool of regulation processes available that can be accessed. Veenman and colleagues (Veenman et al., 2005) mention two reasons for why a production deficiency occurs. Either, the learner doesn't know when and how to execute regulation processes, or task difficulty causes an overload that leads to an inability to execute regulation processes. It is assumed that a production deficiency is more likely than an availability deficiency. The authors investigated the execution of regulation processes with young learners (aged 11-13 years) in the area of problem solving.

Thinking aloud and analysis of cognitive activity during the task revealed that learning performance increased when problem-solving tasks were presented with cues triggering regulation (e.g., “Try to say in your own words what you need to know”). From this finding, the authors claim that most students (even in this young age) have a pool of regulation processes available that can be triggered by cues.

Lack of Regulation While Explaining

Supporting the development of explanations can be beneficial for successful inquiry learning. However, learners often have difficulties when it comes to formulating explanations (Atkinson, Renkl, & Merrill, 2003). For example, learners can be convinced that explanations are not necessary, because they believe that their level of understanding is sufficient. This lack of awareness (Conati & VanLehn, 2000) results in poor explanations or in learners not initiating explanation activities at all. Another example is depicted by Gerjets and colleagues (Gerjets, Scheiter, & Catrambone, 2006). The authors point out that even when a knowledge gap is noticed by a learner, the learner might not be able to utilize explanations effectively in the effort of overcoming the knowledge gap. Shortcomings of these types might be due to lacking appropriate control processes during the development of explanations (Bielaczyc, Pirolli, & Brown, 1995).

One specific aspect that challenges learners is to coordinate their knowledge. This coordination involves taking into account existing knowledge from earlier cycles and new evidence gained from the current experiment. This challenge of appropriately coordinating existing knowledge and new information often leads to weak scientific reasoning (Kuhn, 1993). The integration of explanation activities can be a first step of helping to reflect on the learning process. However, explaining alone might not be sufficient to trigger regulation processes that are necessary to succeed in inquiry learning. This suggests that learners need to be encouraged to regulate their thoughts, thereby taking executive control while developing explanations (Keselman, 2003). Because learners are not expected to employ these regulation processes spontaneously (Veenman et al., 2005), support is needed.

Summary. Learners, especially inexperienced learners, have problems to engage in regulation processes. Several studies included an online assessment of regulation and found that students have problems with respect to planning, monitoring, and evaluation while participating in inquiry activities. Veenman and colleagues (Veenman, Elshout, & Busato, 1994) attribute these problems mainly to a production deficiency (in contrast to an availability deficiency). Problems of regulation become apparent when learners explain their decisions during an inquiry cycle. Several authors claim that shortcomings during explaining are attributed to lacking control processes.

2.4 Support During Inquiry Learning

Research in the past decades has shown that successful inquiry learning is dependent on a variety of factors. It is not the skill alone to run controlled experiments that leads to a satisfying performance of learners (Keselman, 2003). It rather seems that to become a successful inquirer, students need to be competent during all phases of inquiry. Recent developments in inquiry research also seem to make a shift towards research that provides support throughout the inquiry cycle. Inquiry learning environments pursue the goal to engage students actively in authentic scientific activities. In this effort, environments provide tools and possibilities to investigate scientific phenomena such as modeling tools, simulation tools, and scientific evidence. Modeling tools (e.g. CoLab and Stella: de Jong et al., 2002; Steed, 1992) enable the learner to construct and possibly run models, which represent a scientific phenomenon. Learners may represent their understanding of a scientific principle by identifying relevant variables and determining relationships between variables. Simulation tools (e.g. SimQuest and BioBLAST: Joolingen van, King, & de Jong, 1997; Ruberg & Baro, 1999) allow learners to manipulate variables of an existing model, which is usually hidden from the learner. Simulation tools are black box modeling tools, because experiment data are generated based on an underlying model. Simulation tools provide, in comparison with modeling tools, a constrained environment. These constraints are based on the theoretical views of the system designer, who pre-determines a set of variables, which can be manipulated. Tools that emphasize on scientific evidence (e.g., WISE, BGuiLE and Inquiry Island: Linn & Slotta, 2000; Reiser et al., 2001; White et al., 2002), often provide text material, which may complement scientific data or facilities to support online inquiry (e.g., IdeaKeeper: Quintana et al., 2004).

For students to use these tools effectively, they need local support to overcome the problems described in Chapter 2.3.1. This support can be provided in many ways. One way of support is scaffolding. Scaffolds can be various types of support that are used to support learning in situations where students cannot proceed alone but can proceed when guidance is provided (Palinscar & Brown, 1984). Vygotsky's notion (1978) of *the zone of proximal development* is often associated with scaffolds. Quintana and colleagues (Quintana et al., 2004) make a distinction between human and computer-supported scaffolds. Human mentoring involves support by a mentoring person, which could be, for example, a teacher or a peer student. Scaffolds in computerized environments are support devices that enable students to engage in activities that they would not accomplish otherwise. Support with scaffolding character is distinctive from other support, because the goal of the support is to enable the learner eventually to pursue a task without the support. In other words, the goal of providing a scaffold is to become independent of it. A specific characteristic of scaffold tools evolves from this goal: Scaffolds are often combined with a fading mechanism. A support that is faded out over time increases the learner's autonomous behavior during a task (Atkinson et al., 2003; McNeill, Lizotte, & Krajcik, 2006). For instance, if the goal is to enable a learner to develop a syntactically correct hypothesis autonomously, a template can be provided that guides the process of hypothesis development. After gaining experience and understanding the structure of a hypothesis, the learner can use a more superficial template that does not offer the complete structure, but gives only certain suggestions. In a final stage, a learner can be provided with no support at all to see whether he or she is able to formulate syntactically correct hypothesis independently. Yet not all support provided during the development of a hypothesis is a scaffold. It depends on what purpose a support is serving. For instance, if the purpose of a hypothesis support were making sure that appropriate variables are selected, the goal would not be to develop a hypothesis autonomously. Therefore, a fading mechanism does not make sense in this case.

In the following chapter, different types of support (Table 2) that are beneficial during the inquiry process and that tackle problems on various accounts will be presented. They all can either have a scaffolding character or not have a scaffolding character, depending on the goal definition of the support.

Table 2. Types of Support

Types of Support	**Examples**
Inquiry Support	*Basic:* Pre-defined workflows, pre-defined goals (Manlove, 2007) *Advanced:* Pre-structure for specific inquiry tasks in form of template (de Jong & Njoo, 1992), e.g., to facilitate the formulation of a syntactically correct hypothesis (Chen & Klahr, 1999).
Explanation Support	*Meta-level support:* Prompting or requests for explanations → provoking thought
Regulation Support	*Meta-level support:* Prompts and hints for planning, monitoring and evaluation → regulating flow of thought

According to Keselman's (2003) distinction between two forms of instructional support, we can describe the first type of support in Table 2 as inquiry support (which is similar to Keselman's performance support) and the other two types in Table 2 as meta-level support.

Inquiry support is concerned with managing and representing the inquiry activity itself, meta-level support on the other hand is concerned with the management of cognition. Meta-level support can be provided in a generic manner by encouraging learners to reflect during specific stages of an inquiry cycle. Explanation support, for instance, is generic support that aims at eliciting explanations to encourage reflection. Meta-level support can also be provided in a specific manner in form of regulation support. Regulation support offers encouragement to regulate one's own flow of thought.

In the following sections, I will focus on three types of support, namely inquiry support, explanation support and regulation support.

2.4.1 Inquiry Support

Besides evidence that inquiry learning can help learners during their exploration of science, there have also been accounts of questioning the effectiveness of facilitating students to act as scientists (Sweller, Kirschner, & Clark, 2006). Clearly, it can be criticized that putting the student in the situation of a scientist with equivalent tools, methods etc. is not sufficient to warrant students' understanding of scientific phenomena. Research has shown that providing computer-based environments with minimal guidance or basic support only is not helpful (Mayer, 2004).

Defining Inquiry Support

Inquiry support provides structure or information to make a specific task or an activity more manageable. This form of support is called inquiry support because it enables the learner to pursue activities that are necessary to succeed in the endeavor of completing an inquiry cycle. There are two levels of inquiry support: On a basic level, inquiry support is concerned with breaking down an inquiry activity into steps (also called process management support in Quintana et al., 2004), by, e.g., providing an activity structure. Basic inquiry support is directed towards completing the inquiry cycle itself. At an advanced level, inquiry support involves guiding the learner within a specific task of the inquiry cycle.

Basic Inquiry Support

Students, who are not experienced in using inquiry as a method in science need to be supported because the process of inquiry is not yet well understood. Therefore, an activity structure (sometimes called *process model*, see Manlove, 2007) on a macro-level may help to make sequences explicit to the learner. Such an explicit activity structure can guide the learner from one inquiry phase to the next and hence establish a pre-defined workflow. On the other hand, an explicit activity structure can restrain a learner from adapting the inquiry cycle when it is needed and thus lead to a strict following of the inquiry cycle without trying to engage in understanding the structure of the inquiry process. To support an inexperienced learner but to allow at the same time for some flexibility in adapting and actively making sense of the inquiry cycle, a scaffolding mechanism can be implemented to adapt to the learner's needs. For instance, White and Frederiksen (1998) presented learners with an explicit structure of the inquiry cycle. As students gained more experience, this structure was adapted promoting a more independent inquiry cycle: In the beginning of an investigation, the inquiry cycle was heavily scaffolded. Scaffolds in this case consisted of examples, which showed in detail how an experiment could look like. Thus, the students designed an experiment on their own being guided by existing examples. Towards the end of an investigation, students made experiments and formulated research questions on their own. Hence, the students became independent of the scaffolds and didn't need them anymore. A novice inquiry student might need a sequential process as a road map at the beginning in order not to get lost during the experimentation process. Later on, the student can engage in specific phases of the inquiry cycle several times or leave out a phase. The student then makes a more autonomous use of the inquiry cycle. In sum, the phases of inquiry should be made explicit especially in the beginning of an inquiry cycle; however, macro-level support should not prevent the learner from adapting the inquiry cycle flexibly.

In computer-supported learning environments, macro-level support is an important component to make the activity structure explicit. Existing learning environments have accomplished this in various way as can be demonstrated by comparing WISE, Co-Lab, and Inquiry Island: A procedural approach was implemented by *WISE* (Linn & Slotta, 2000) to represent the inquiry activity structure (Figure 5). *WISE* stands for Web-based Inquiry Science Environment. It is an inquiry learning environment that allows to author and run projects in more than 11 subjects. It currently includes 89 projects. For every project run, *WISE* offers a sidebar that contains a procedural step-by-step outline. The outline consists of evidence links, prompts, hints and other components, which can be adapted by the teacher. Clicking on the link in the sidebar opens a new page in the main frame of the environment. If a learner is going back in the activity outline displayed in the sidebar, the system indicates that these pages have been visited already. Similar, if a learner skips steps he or she will be reminded, that the current activity step has not been visited yet. Besides the procedural outline, the teacher can also integrate so called looping activities. Loop activities will not be displayed in the side bar of *WISE* and allow therefore a more flexible, non-procedural activity structure. The loop activity structure is recommended for activities that don't necessarily build on each other.

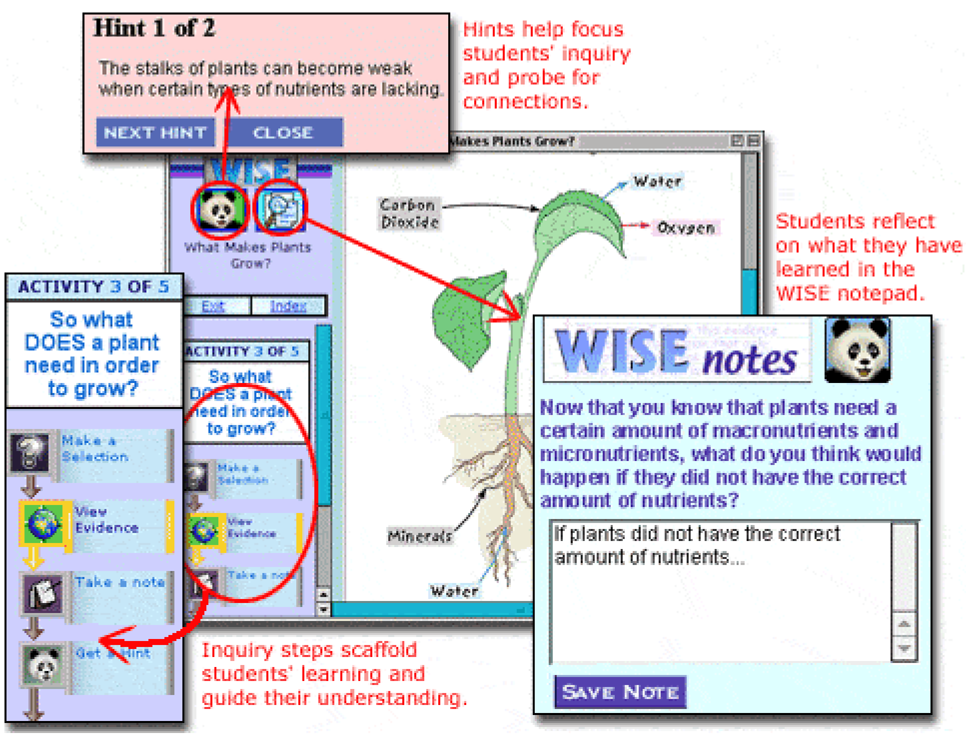

Figure 5. Screenshot of *WISE* (Retrieved from wise.berkeley.edu)

In contrast to this procedural approach is the implementation of an activity structure in *Co-Lab* – Collaborative Laboratories for Europe (Joolingen van et al., 2005). In *Co-Lab (*Figure 6*)*, the phases of inquiry are represented as part of a building metaphor. Every phase (exploration, hypothesis generation, experimentation, and evaluation) represents a separate building (Hall, Theory, Meeting, and Lab), which students can visit. The building metaphor is a flexible approach, which enables students to move back and forth between rooms. However, because every activity is separate from each other, a learner (metaphorically speaking) needs to move into another building to engage into another inquiry phase. Thus, a learner gets lost very easily (as opposed to *WISE*, where a learner has the sidebar always visible to move and to gain location awareness). Manlove (2007) has designed a procedural support for *Co-Lab*, which is included in the so-called Process Coordinator. The Process Coordinator includes a goal tree, which outlines the phases of inquiry and once a learner selects a goal (e.g. collecting information), hints and help files provide micro-support for the specific phase in which a goal is pursued. Every sub-goal in the goal tree of the Process Coordinator can be revisited and the reports can be reviewed via a sequential history view.

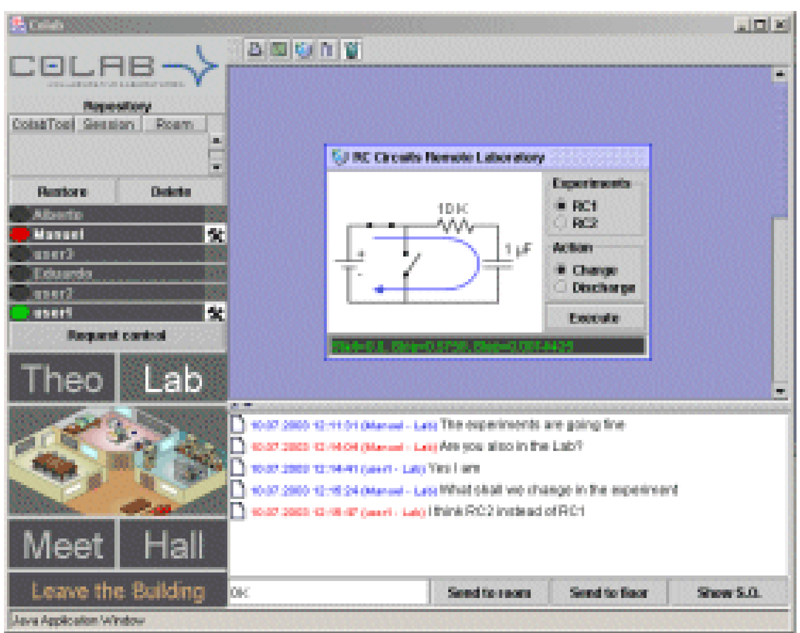

Figure 6. Screenshot of Co-Lab Interface (retrieved from http://www.co-lab.nl)

In the software *Inquiry Island* (Eslinger, White, Frederiksen, & Brobst, 2008) the activity structure provides a flexible procedural approach. In contrast to *Co-Lab*, a step-by-step inquiry structure is provided. However this structure is flexible enough to switch freely between different phases facilitating the iterative nature of inquiry. Every inquiry phase can be selected using a tabbed interface (Figure 7) that allows the user to switch between hypothesis phase, experiment phase etc. The software is domain independent; hence, it can be used for various science topics (e.g., genetics).

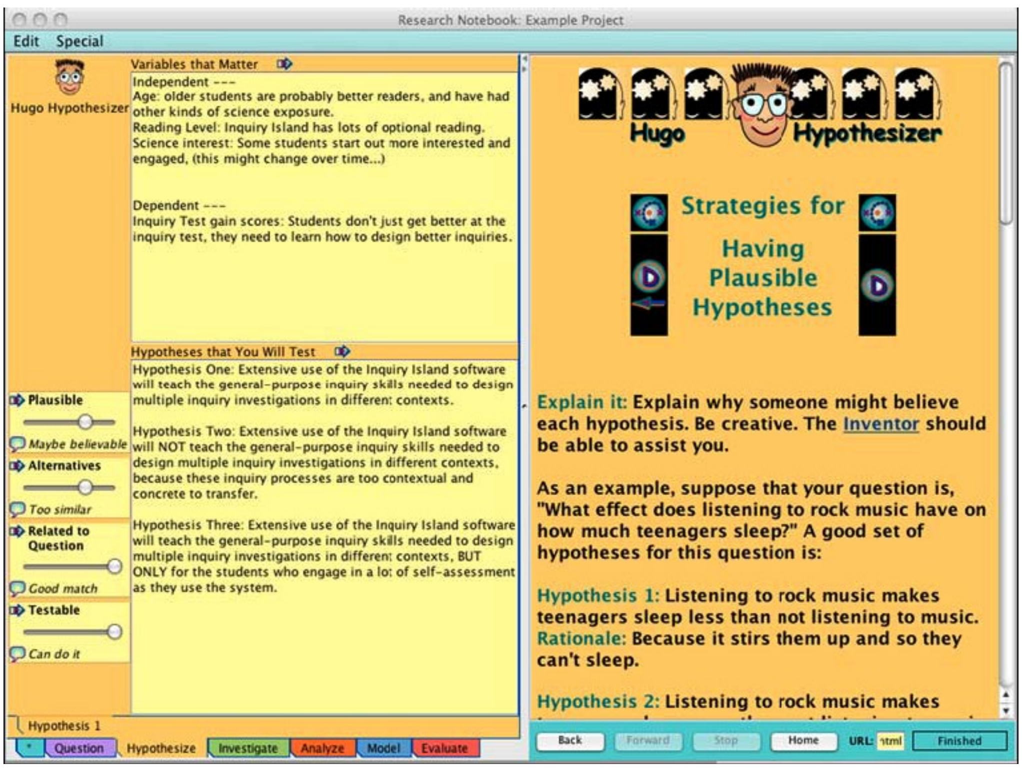

Figure 7. Screenshot of the Inquiry Island Interface (Eslinger et al., 2008)

In sum, all environments described above have a macro-level activity structure that represents the phases of inquiry within the interface of the respective environment. The macro-level inquiry support within each environment differs with respect to the flexibility of the activity structure that is represented in each environment. Each macro-level inquiry support is flexible enough to skip phases and to go back to phases that have already been visited. However, not every macro-level support facilitates the iterative nature of inquiry. For example, in the *WISE* environment, it is not foreseen to jump back and forth between activity steps. The Process Coordinator, an add-on to *Co-Lab*, visualizes the iterative nature showing a cycle, but the goal tree, which guides the learner through the phases of inquiry, is offered in a sequential manner. With respect to the cyclic nature of inquiry, *Inquiry Island* turned out to have the most facilitative macro-level support. The cycle is represented visually and, hence, it suggests the learner to start with a new experiment when finishing one. This cyclic nature can be implemented in *WISE* as well using the "looping activity", but it is not inherent in the outline displayed in the sidebar.

Advanced Inquiry Support

Advanced inquiry support takes place at a micro-level. Advanced inquiry support provides tools for learners to guide the learner within a specific task. During the orientation phase, tools should facilitate a global expression of ideas. During the hypothesis phase, tools should narrow the view towards principles and variables that are related to a specific experiment. The experimentation phase should offer tools to help learners to manipulate variables systematically. During the analysis/results phase, the learner should be enabled to overcome problems with respect to coordinating the hypothesis with new gained evidence from running experiments. During the new question phase, the learner should be supported in the endeavor of using newly gained knowledge to develop a new hypothesis.

Orientation phase. In general, external representation activities (Toth et al., 2002) can be beneficial for learners to express their ideas about the phenomenon of investigation. During the orientation phase, external representation activities can facilitate the identification of relevant variables and relationships between variables. One example of an external representation activity is model building. Model building allows learners to represent their knowledge about variables externally. Depending on the type of modeling activity, learners can represent the relationships between variables on different levels of precision. Quantitative modeling requires specifying the values and unit of every variable. Qualitative modeling demands less precise representation of relationships. In both cases, learners can revisit their models in the beginning of a next inquiry cycle and modify it, taking into account the new experiences from the past experiment.

The *Co-Lab* environment (Joolingen van et al., 2005), for instance, supports learners during an orientation phase by allowing them to sketch qualitative models to represent their knowledge about variables. Model sketching takes place at a lower level of precision than actually running a model. In *Co-Lab,* the model sketching activity is carried out with a modeling tool based on system dynamics, in which variables need to be described by specifying relationships (Figure 8). In order to specify relationships during model sketching, learners don't need to fill in exact numbers (as it is necessary in quantitative modeling), but they need to represent relationships using dichotomous symbols (+/-) or graph-based symbols (exponential, linear etc.).

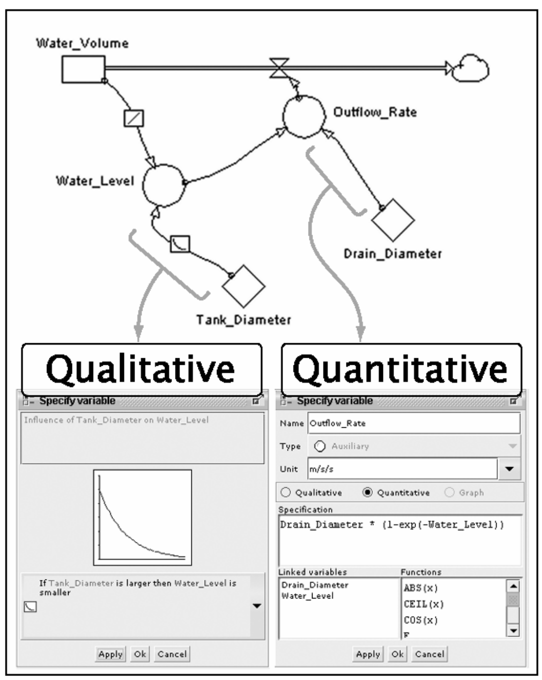

Figure 8. Qualitative vs. Quantitative Modeling in Co-Lab (Manlove, 2007)

Engaging students in model building can be a helpful activity to facilitate reasoning processes during an inquiry cycle (Löhner et al., 2005). It can also be assumed that modeling activities at different levels of precision lead to a different engagement in information processing during the inquiry cycle. Dichotomous relationships are easier to determine, but they are less precise and may require the learner to engage less in information processing. Graph-based representations display relationships more precisely and require the learner to think *how* two variables are related to each other. The practice of sketching a model prior experimentation has another benefit: It prepares the learner to state a research question. Exploring the problem space through model building can support the learner in their endeavor of investigating a phenomenon, but it also puts high demands on the learner. Therefore, to limit the problem space, a pre-selection of relevant variables might facilitate the learner to define an appropriate research question. This makes the modeling activity much easier, because the learner needs to focus only on determining the relationships between variables. Yet, by taking load from the learner by pre-selecting relevant variables, the learner will have less opportunity to explore the phenomenon.

Hypothesis phase. Hypothesis generation is a central aspect within the inquiry cycle. There is empirical evidence that supporting hypothesis generation is beneficial for learning (Wirth, 2003). Wirth (2003) refers to a study by Schröter (2001), in which an analysis of think aloud protocols revealed that students who developed hypotheses outperformed students who didn’t develop hypotheses. Various aspects can be focus of support with respect to developing a hypothesis. For example, learners can be supported to formulate a syntactically correct hypothesis.

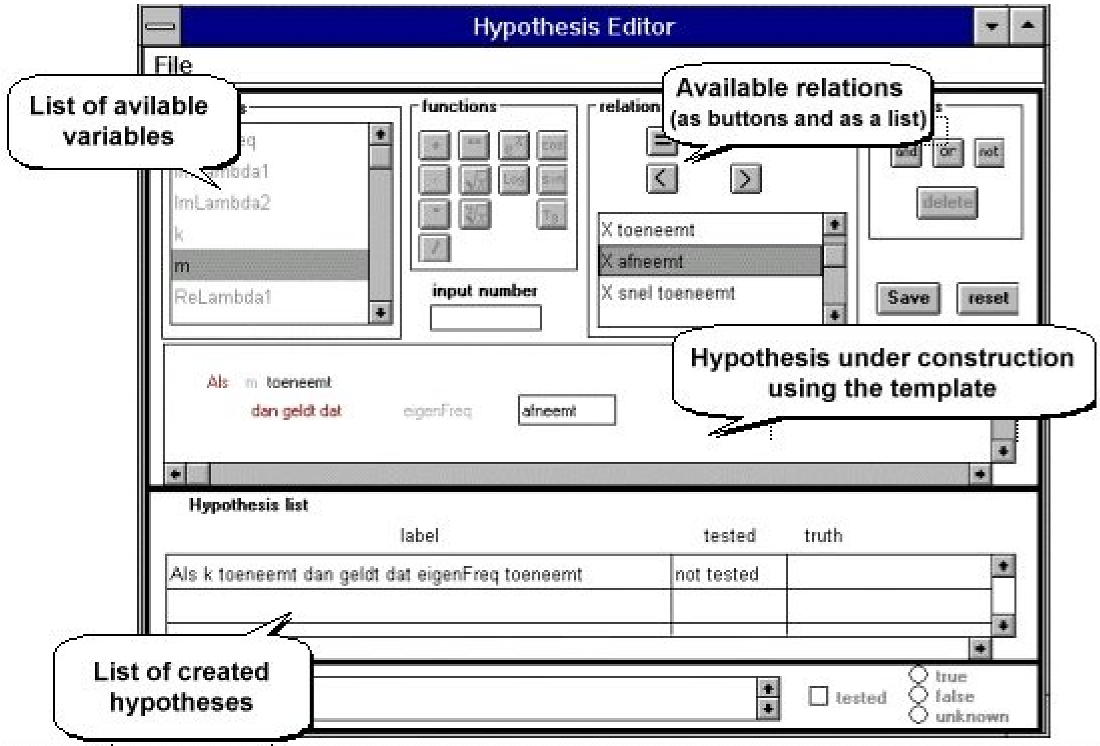

Figure 9. Screenshot of Hypothesis Scratchpad (Joolingen van & de Jong, 1993).

Van Joolingen and de Jong (1993) developed a scratchpad that can be used as a template to guide through the process of developing a hypothesis (Figure 9). The template provides basic structural components of a hypothesis. The components consist of pre-selected variables, relations, and conditions that can be chosen from a drop-down menu. In their study, variables were provided on a more general level with respect to the underlying conceptual model (Joolingen van, de Jong, 1993). Possible relations and conditions were presented, among which the learner could choose. Conclusions from the study, which compared different levels of structure within a hypothesis scratchpad, imply that thinking of more precise relations between variables is beneficial, but that providing a hypothesis scratchpad including a structured template alone does not lead to higher performance on a posttest. Another approach was taken by Njoo and de Jong (1993) with respect to supporting the correct generation of a hypothesis. The authors provided a pre-defined hypothesis and found that it had a positive influence on learning process and performance.

Another aspect of support is related to the learner's avoidance to disconfirm a hypothesis. Writing down a hypothesis that can be compared with experiment data is helpful but doesn't provoke a cognitive conflict (Limón, 2001). Learners tend to interpret their experiment data in a way to confirm the hypothesis formulated earlier. In other words, matching results and hypothesis seems to be an implicit goal of students when running experiments. Therefore, a more precise representation in form of a graph (than just an articulation of a hypothesis) can enable students to compare hypothesis and experiment data directly. A graph-based prediction can be used later in the process as an overlay to the collected experiment data. If the graph that has been drawn during the hypothesis phase does not resemble to some extent the graph resulting from the data collection, a learner is forced to think of an alternative explanation or at least become aware of the gap between both graphs.

Inquiry Island supports the generation of a hypothesis by providing advisors. First, the learner is asked to use sliders to rate the believability and testability of their hypothesis. Then an advisor suggests on how to proceed (e.g., going back to the question formulated earlier) based on the learners ratings. The hypothesis advisor is just one of many advisors during an inquiry cycle in *Inquiry Island*, which guide the learner through the phases of inquiry.

Experiment phase. Experimentation requires systematic manipulation of variables. One possible approach to support learners in systematically altering variables is described by Tschirgy (1980) as the *VOTAT* heuristic (see also Controlling Variable Strategy in: Chen & Klahr, 1999). *VOTAT* stands for *Vary One Thing at a Time* and it suggests varying one variable while all others are held constant. A premise of using this heuristic is to be able to determine the dependent and independent variable when running an experiment. The advantage of controlling one variable is that observed changes in an experiment can be attributed to the one variable that has been altered. Empirical findings show that systematic behavior while testing hypothesis has a positive impact on learning performance (Chen & Klahr, 1999). Keselman (2003), for instance, supported students' understanding of multivariable causality by a) practicing, b) observing a teacher modeling and c) not supporting how to design good experiments. Findings indicate that both types of support were beneficial and that especially observing teachers modeling a good experiment design was advantageous with respect to knowledge gain and experiment-design skill acquisition. Supporting learners in systematically testing hypotheses for instance through encouraging the *VOTAT* heuristic has been successfully implemented in various learning environments. For instance, Veermans and colleagues (Veermans, Joolingen, & de Jong, 2006) compared implicit and explicit support of experimentation heuristics such as *VOTAT* in rich simulation-based environments. Explicit support included the offer of explanations and justifications why these experimentation heuristics were useful. No differences were found regarding knowledge performance and strategy acquisition, but there were indications that the explicit heuristic condition was advantageous for weaker students. Limitations of applying the *VOTAT* heuristic become apparent in inquiry investigations that require changes of several variables, for example when measuring interaction effects (Zohar, 1995). Therefore, support of variable control needs to take into account these limitations.

Analysis/results phase. Learners' problems that arise while drawing conclusions often have to do with coordinating new findings with the hypothesis (Chapter 2.3). Several learning environments have been shown to be successful in offering support for learners to draw valid conclusions.

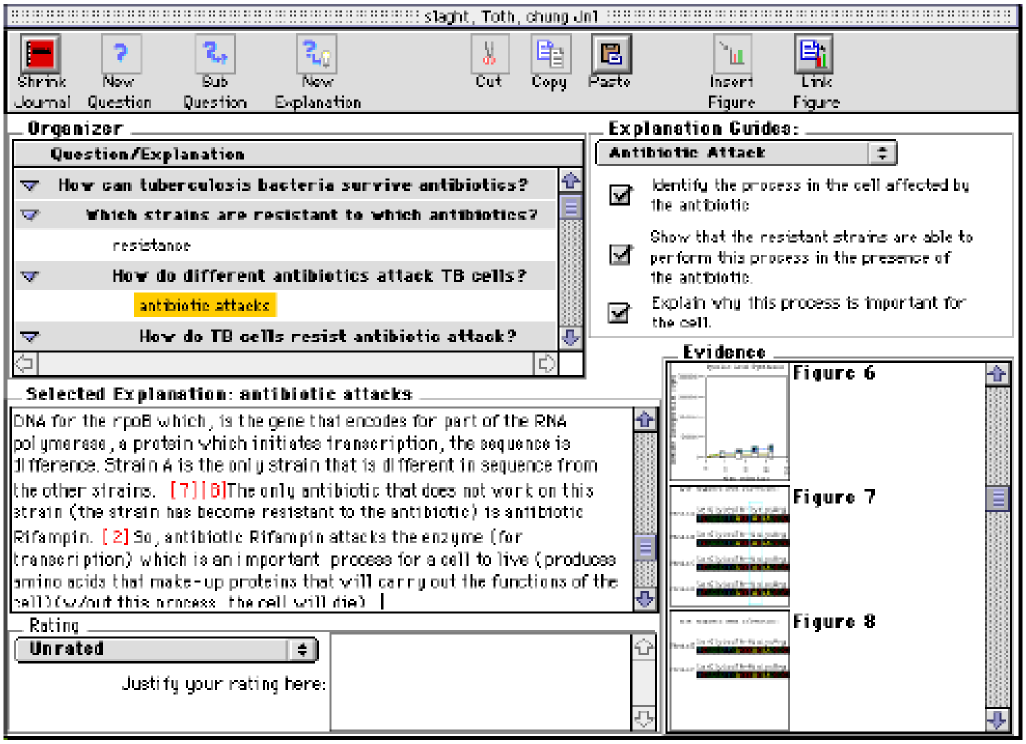

Figure 10. Screenshot of Explanation Constructor in BGuile (Sandoval, 2003)

The learning environment *BGuile* (Sandoval, 2003) for instance, provides specific support, which is available throughout the inquiry process (Figure 10). *BGuile* is an inquiry environment, which allows learners to investigate various phenomena in the domain of Biology, such as the investigation of a crisis in an eco-system. A journal template called *Explanation Constructor* constraints students and helps them formulate new explanations in direct relation to evidence that has been collected. In addition, it includes domain-specific information with respect to building blocks of an explanation in the area of evolution and domain-related prompts. Findings by Reiser and colleagues (Reiser et al., 2001) indicate that students were able to articulate conclusions involving important components of natural selection explanations, which is in opposite to reported difficulties when articulating explanations with respect to variation of natural selection.

The inquiry environment *KIE* - Knowledge Integration Environment (Linn, 1995) is a predecessor of (and therefore similar to) *WISE* (Linn & Slotta, 2000), focusing on exploring scientific principles using the Web.

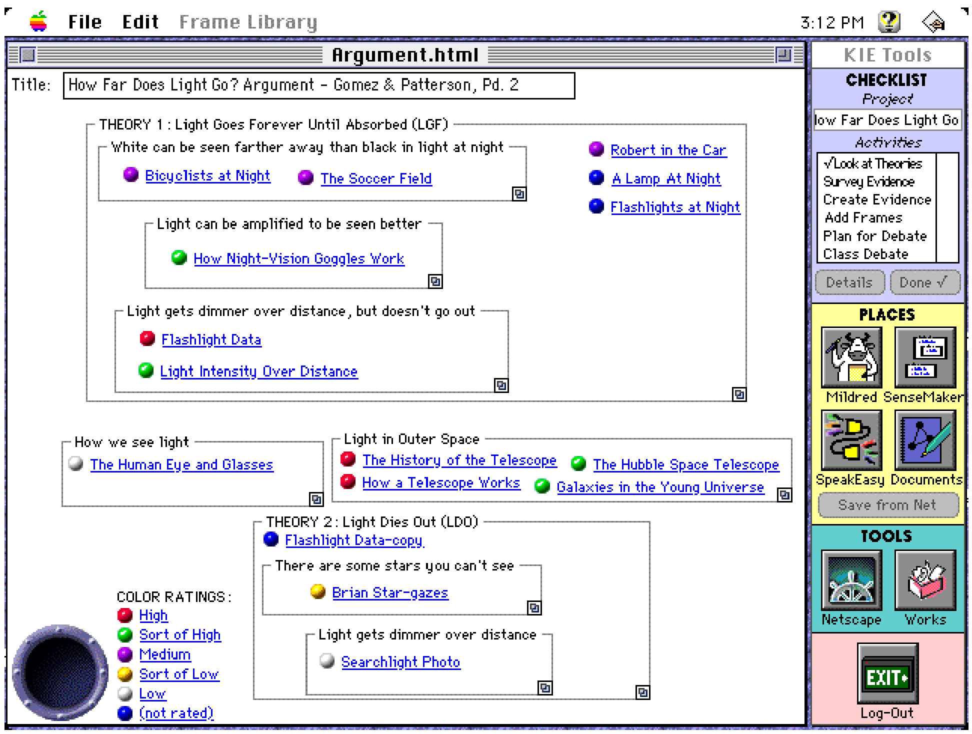

Figure 11. Screenshot of SenseMaker Tool in KIE (Bell, 2000)

KIE offers a specific component called *SenseMaker* (Bell, 2000), which supports the learner to organize evidence (Figure 11). As students collect evidence on the web, they organize their evidence into categories within the *SenseMaker* tool. Bell found that using *SenseMaker* helps students by visualizing the process of organizing evidence into claims. Moreover, results indicated that students developed a greater understanding about the purpose of scientific argumentation.

New question phase. Students need to be supported to formulate new questions. Specifically, students should be supported to formulate a question as part of a broader investigation goal. Hence, an environment should provide support to feed newly gained knowledge into the next inquiry cycle. *Inquiry Island* (White et al., 2002), for instance, encourages the learner to formulate a new question after finishing the previous experiment. Initial questions that have been formulated by students are important and should not be completely rejected, but they need to be broken down into precise research questions that specify the conditions of the experiment. For example, the question "How can humans survive if they live on a remote planet" needs to be broken down into sub-questions. One testable question could be „What type of and how many plants need to be grown to feed 100 people?" Reminders can be implemented in a learning environment via sentence opener and hints (Linn & Slotta, 2000).

Summary. Inquiry support aims at making an inquiry activity more manageable. Inquiry support can be provided on a basic level by providing an explicit activity structure. Inquiry support can also be offered on an advanced level by supporting specific tasks within the phases of an inquiry cycle.

2.4.2 Explanation Support

Defining Explanation Support

Explanation support is meta-level support and aims at promoting reflection. Explanation support provides no specific direction but provokes thought. It may be achieved by asking generic questions (e.g., "What have you found out?") or by providing explanation prompts (e.g., "Please explain", "Please tell"). Explanation support may be offered during specific inquiry phases. It aims at making thinking processes explicit that are usually covered (Scardamalia & Bereiter, 1985).

Explaining during inquiry can facilitate the learner to succeed not only in running a series of experiments successfully, but also, and more important, to benefit from this activity as a learning experience. In general, a goal of science learning is to engage students in scientific reasoning by formulating coherent explanations. Yet, learners, especially novices, cannot be expected to give explanations spontaneously (Sandoval, 2003). Offering an inquiry environment that fosters the articulation of explanations allows learners to represent their decision-making processes externally as well as their newly gained insights. Several inquiry learning environments offer means to engage in articulating explanations (Lajoie, Guerrera, Munsie, & Lavigne, 2001; Manlove, 2007; Reiser et al., 2001). Non-directive support may include explanation scratchpads, help-seeking possibilities, and hints, which do not actively push the learner to engage in explanation building. In explanation-driven inquiry learning, non-directive support (Joolingen van & de Jong, 1991a, 1991b) alone seems not to lead to the expected learning outcomes and improvement of generating explanations. Directive support, on the other hand, has shown to lead to better learning outcomes and quality of explanations. Directive support can be provided in form of prompts (Moreno & Mayer, 2005).

Prompting learners to explain during a task has been found to affect the quality of information processing in contrast to thinking aloud. Yet, think-aloud methods only tap content from working memory without requiring additional information processing (Ericsson & Simon, 1993; Veenman, Elshout, & Groen, 1993). Hence, verbalizing via think aloud does not affect working memory. Therefore, the think aloud method cannot be used to improve performance. However, prompts specifically aim at affecting the quality of information processing and do so by changing the quality of information processing. If the goal is to affect the quality of information processing, explanation prompts are more suitable than think-aloud methods.

Existing Research on Explanation Prompts

Substantial research has been focusing on supporting reflection by eliciting explanations using explanation prompts while studying instructional material (Chi, de Leeuw, Chiu, & LaVancher, 1994; Hausmann & Chi, 2002). Although the nature of the task of studying instructional material is quite different from running experiments, findings about prompts are still relevant. Findings indicate that learners receiving explanation prompts are more successful with respect to learning in comparison to those who do not receive explanation prompts (Chi et al., 1994). Explanation prompts are simple, content-free prompts, which generically ask students to explain. Hausmann & Chi (2002) conducted two experiments in which students were reading instructional material about the blood-circulatory system. Students in a spontaneous explanation situation were compared with students in a prompting situation. Students in the spontaneous explanation situation had the possibility to explain but were not prompted to do so. Students in the prompted condition were explicitly encouraged. Results show that students in the prompted condition increased the number of typed explanations and showed learning performance than students in the spontaneous explanation condition. This finding is in line with Renkl and colleagues' (Renkl, Stark, Gruber, & Mandl, 1998) findings that prompted explanations are more effective than spontaneous explanations while studying worked-out example material.

The studies reported above have shown that self-explanation prompts are effective, but there is also evidence that explanation prompts are not beneficial to all students (Aleven & Koedinger, 2000). In many cases, learners have problems even if explanations are elicited by explanation prompts (Renkl, 2002). Therefore, it is necessary to ask whether explanation prompts in inquiry learning will be effective.

Differences of effects can be expected depending on the nature of the task in which prompts are provided. In the studies reported above, prompts were provided during sequences in which students were expected to read a text. The nature of reading a text does not necessarily engage a learner in reflective processes. Often, reading may result in a passive process if learners are not encouraged to engage in reflection. Reflection triggered by additional explanation prompts may be the cause leading to those strong effects on learning performance reported above. In the case of inquiry learning, the nature of the task requires students to engage in active knowledge construction by developing hypotheses and producing evidence that might confirm or disconfirm their initial hypothesis. Reflection is triggered automatically during these activities. Therefore, explanation prompts may not lead to the same results in inquiry learning compared to reading text. Moreno and Mayer (2005) provided some answers to this problem by investigating effects of a special type of interaction and elaborative interrogation in a simulation-based inquiry environment. In the first study, learners in the experimental condition were asked to explain their provided answers while designing a plant that can survive on a fictional planet. Interactivity was increased by allowing students to provide answers to questions that were posed by the system. If interactivity was decreased, students were not allowed to provide answers. Instead, the system provided the answer. The authors found that learners did not benefit from explanation prompts with respect to learning: A knowledge test including items assessing retention showed no significant difference between the group that received explanation prompts and the group that did not receive explanation prompts. With respect to a problem solving test, no difference was found either. In a second study, it was tested whether the low interaction increased the effect of the explanation requests. Indeed, findings show that crossing explanation support (asking participants to provide an explanation) and interaction (high interactivity vs. low interactivity) leads to significant learning effects with respect to retention and with respect to problem solving in the condition of no interaction and explanation support. In sum, these findings demonstrate that the nature of the task may decide whether direct explanation support leads to learning or not. Providing explanation prompts is effective during tasks that don’t require any interaction, such as studying instructional material (e.g. reading a text). The same accounts for providing explanation support in a simulation-based learning environment that requires low interaction. The benefit from explanation support is absent if a learner engages in a task that requires this special type of interaction.

Assessing the Quality of Explanations

Explanation prompts aim at eliciting explanations that do not only engage in deeper processing but also make visible whether learning has taken place or not. On the one hand, assessing the quality of explanations can give insights whether the provided support functioned as intended (treatment check). On the other hand, the quality of an explanation can be used as a performance indicator to measure learning gain. In the studies by Moreno and Mayer (2005), learning outcome was assessed using a retention test and a problem-solving test to gain insights with respect to learning gain. The problem-solving test included questions that required students to explain the effect of specific conditions of a plant (e.g., “Why do you think that the plant designed will flourish in the environment that you chose?”). The explanations were scored as correct or incorrect and used as an indicator for assessing students’ learning gain with respect to problem solving in the respective conditions. Students received full score disregarding the quality of their explanations as long as the relevant information was stated. Yet, the quality of explanations was taken into account when analyzing explanations that were articulated during the learning process (in the respective conditions that included explanation support). The correctness was determined by comparing a students’ explanation with the correct explanation provided by the learning environment. If a student referenced a concept that was included in the learning environment, the explanation was scored as correct. If a student provided an explanation that was based on a misconception or if a student did not include any reference to a concept, the explanation was scored as incorrect.

Besides the studies of Moreno and Mayer (2005), several authors (eg., Sandoval, 2003; Veenman et al., 1994) have shown that the quality of a learner’s verbalizations can shed light on their level of understanding. Specifically explanations became a focus of investigation, because, unlike actions, they require the learner “to articulate some model that accounts for the phenomenon” (Metz, 1991, p. 785). The explicit application of newly acquired information within an explanation can indicate that an integration of knowledge has taken place. When students explain the underlying reasons of why, e.g., a hypothesis was accepted or rejected, students use explanations that touch the underlying principles of the phenomenon to different degrees depending on their existing knowledge and experiences from previous experiments. Therefore, explanations have become a common performance indicator because taking a closer look at learner’s explanations can reveal problems of understanding the phenomenon.

Sandoval (2003) investigated learners’ explanations focusing on two aspects that are important criteria for evaluating explanations: causal coherence and evidential support. Explanations can be characterized as causally coherent if a learner articulates causal mechanisms and if chains of causes and effects within these mechanisms are coherent. Sandoval (2003) determined the coherence by decomposing explanations in propositions containing causes and effects and analyzing the causal relations between propositions. Explanations were regarded as less coherent if less causal relations were found in comparison to the overall amount of propositions. The second criterion, evidential support, refers to the coordination between data and explanations. Good explanations are warranted by multiple instances of data (e.g., field notes, graphs, tables.).

Prominent research that focuses on the quality of explanations comes from the area of problem solving, often by deploying worked examples to engage students in learning (Chi et al., 1989; Schworm, 2006). Chi and colleagues (Chi et al., 1989) determined the quality of explanations of good and poor problem-solvers and distinguished them by determining the success of solving physics problems using worked-out examples. Before solving the problems, students participated in a knowledge acquisition phase to learn about mechanics from reading text chapters. During problem solving, students were asked to verbalize their learning process. An analysis of the verbalizations showed that good problem-solvers made sense of aspects that they tried to understand by inferring implications in addition to the implications that directly derived from the textbook or the worked examples. The authors also distinguished between structures and content. Analysis indicated that regarding the structure, good problem-solvers provided justifications and meaning to aspects that they tried to understand. Regarding content, good problem-solvers developed examples that were related to principles in the text that they read beforehand. Above all, an analysis of the quantity of explanations showed that good problem-solvers produced significantly more explanations than poor problem-solvers.

In a subsequent study, Chi and colleagues (Chi et al., 1994) distinguished between high and low explainers by ranking students according to the number of inferences that were included in explanations. Eighth grade students were asked to read a text about the human circulatory system and were then prompted in the treatment condition to self-explain. An utterance was coded as explanation if it included information apart from the information that was provided in a text. Hence, utterances did not count as explanation if they only included paraphrases (synonymous words instead the ones in the text) or monitoring statements.

Criteria to analyze the quality of explanations are often used as a treatment check during the learning process; they are rarely used as evidence for learning gain. For instance, Moreno and Mayer (2005) analyzed the quality of explanations during the learning process but not through a dependent variable. Yet, as a performance indicator, the quality of explanations should be measured outside of the treatment conditions.

Criteria to Assess the Quality of Explanations

Several studies have been described that employed different criteria to distinguish between good and poor explanations. In the following, important characteristics of explanations will be summarized. The characteristics were commonly used as criteria to assess the quality of explanations. The criteria are specifically relevant in inquiry learning, because they indicate that scientific reasoning has taken place.

Causality. One important aspect related to scientific reasoning is causality (Lajoie et al., 2001). While learners develop explanations, they are expected to engage in scientific reasoning to understand relationships of relevant variables. This identification of a causal relationship happens when an individual finds a covariation between events (Hume, 1988). A perfect covariation, for example, exists when the same cause and outcome always appear together. The presence of causality can be taken as an indicator for high quality of an explanation. Yet, plain descriptive explanations, for example, are an indicator for a low quality explanation. When learners write descriptive explanations, they stick close to what is observed without describing the causal relationship between variables. For instance, a learner's explanation might describe the shape of a prediction graph only (e.g., "The blue graph goes up at first, and then flattens out after a while") or relate variables superficially to each other (e.g., "The red line does the same in the beginning, but continues going up"). On the other hand, an indicator of scientific reasoning can be, for example, the presence of if-then clauses linking scientific concepts in an explanation concerning the relationship of two variables (e.g., ”If light hours go up, biomass production goes up”).

Complexity. Complex explanations include references to other relevant variables besides the one that is controlled and besides the dependent variable. Relevance in general is an important factor to judge an explanation (Keil, 2006), but especially the presence of relevant variables seems to be an important aspect of explanations in an inquiry cycle. To give an example, let us imagine a student investigating the effect of CO_2 on biomass production. An explanation of low complexity is: “CO_2 affects plant growth only to up a certain point, because there will be a saturation point at which the plant cannot take in more CO_2.” In contrast, an explanation of high complexity will not consider only the independent and dependent variable but also other variables that are not directly controlled in the experiment. In an explanation of high complexity, the student adds the following statement: “There are other variables that affect the intake of CO_2. One is for example the presence of wind. If there is a storm, plants take in less CO_2”. The relevant variables included in an explanation can be an indicator for the quality of an explanation (Coleman, 1998). In inquiry learning, students conduct scientific experiments that consist of manipulating one variable while holding other variables constant. Knowledge about the dependent and independent variable is necessary to run the experiment, but awareness of causal relationships with other relevant variables is necessary to make inferences.

Consistency. An indicator of a good explanation is its consistency. Consistency refers to logical relations and non-contradictory descriptions (Savelsbergh, De Jong, & Fergusen-Hessler, 1997). Explanations can be inconsistent in several ways: They can be consistent in themselves but inconsistent with the principles of the phenomenon. A learner might give an explanation to justify a hypothesis that is referencing a correct, yet irrelevant aspect of a scientific principle (e.g., “Biomass will not increase after a while when giving more CO_2 to the plant, because light is the energy source for the plant”). Moreover, explanations can be consistent in relation to principles, but show inconsistencies with the data at hand. Hence, the relation between data and hypothesis can reveal the consistency or inconsistency of explanations made (Toth et al., 2002). Consistent explanations describe accurate relationships between data and hypotheses. Students might either refute (pointing out an inconsistent relationship) or support the established relationship between hypothesis and data. For example, in the analysis/results phase of an inquiry cycle, a learner might reference a relevant principle, but he or she might not be able to integrate the data results consistently (e.g., "CO_2 will lead to a constant increase of biomass production, because both CO_2 and light are important things for photosynthesis"). An example of referencing correct principles that are consisted with data is: "The edible biomass will increase until CO_2 intake reaches saturation, because when the plant doesn't need CO_2, the plants will close its stomata."

Summary. Findings from studies in the area of reading and studying instructional material suggest that prompting for explanations is beneficial in comparison to no prompting. However, detailed analyses show that, when prompted, not all learners are capable of articulating correct explanations (Renkl, 1997). In fact, in some domains only few students formulate correct explanations (Aleven & Koedinger, 2000). Findings from multimedia learning research suggest that the nature of the task in which students are engaged in influences the effectiveness of direct explanation support. Hence, explanation support is effective only under specific conditions. In the case of inquiry learning, it seems that additional help may be needed besides direct explanation support to leverage not only reflective processes during inquiry activities. A positive effect of direct explanation support can be assumed for inquiry leaning as well, but explanation prompts might not be sufficient. Therefore, explanation support via prompts should be augmented. Criteria for assessing the quality of explanations have been described. These criteria are especially relevant in the area of inquiry learning because they indicate whether learners engaged in scientific reasoning.

2.4.3 Regulation Support

Providing support during explaining has been promoted by various researchers. Giving effective support has produced mixed results in various domains. Several approaches such as providing feedback (Conati & VanLehn, 2000) or self-explanation prompts (Berthold, Eysink, & Renkl, 2009) have been found to be successful, while others like providing instructional explanations (Hilbert, Schworm, & Renkl, 2004) have not been found superior in comparison to using explanation prompts alone. Especially in inquiry learning, the focus of support should not be on providing immediate feedback or ready-made explanations. Rather, students should take control by themselves with respect to their progress during learning and evaluating the validity of their explanations. However, learners often don't engage in regulation processes sufficiently. Therefore, support during explaining should help to overcome this deficit by providing regulation support.

Defining Regulation Support

Regulation support is meta-level support that aims at improving a learner's performance by fostering effective execution of regulation processes. Regulation support provides, in contrast to explanation support, directions regarding the way control should be executed. This regulation support may be tailored to inquiry tasks and it may be emphasized during different phases of the inquiry cycle. It is provided to regulate more effectively ones' own flow of thoughts during orientation, during formulating meaningful hypotheses, while designing controlled experiments or while drawing conclusions. Regulation support targets the improvement of scientific reasoning processes because of a more effective management of and engagement in regulation processes.

As described in the previous chapter, explanation support in form of prompts has been found to be beneficial during inquiry learning in terms of learning performance. Explanation prompts encourage to make thinking processes explicit and to provoke thought, but learners might lack the ability to regulate themselves therefore the environment needs to take over this responsibility to some extent. This type of support can be called *regulating support* because it includes providing pre-structured workflows, which aim at taking the burden from the learner to regulate without guidance. Regulating Support is different from regulation support, because the first aims at relieving the learner from regulation and latter aims at activating regulation. Studies investigating the first type will not be reported here but were reported in Chapter 2.4.1.

Another approach to support learners during the learning process is to utilize prompts that are related to content (Aleven & Koedinger, 2002; Berthold et al., 2009; Mackensen-Friedrichs, 2004). Content-related prompts include content specific information and aim at eliciting content-specific knowledge (Lin, Hmelo, Kinzer, & Secules, 1999; Sandoval, 2003). This approach is different to the content-independent approach pursued in this dissertation; therefore, it will not be examined further.

In this dissertation, regulation support refers to those types of support that activate regulation processes and that don't relieve the learner from regulation. The goal of regulation support is to overcome a production deficiency (Flavell, 1979; Veenman et al., 2005). The employment of this kind of support presumes that the learner draws from a pool of regulation processes available, which he or she only needs to be reminded of in order to activate them. Regulation support may include prompts, which can be offered as cued questions (e.g., King & Rosenshine, 1993), hints (Linn & Slotta, 2000), reminders (Veenman et al., 2005) and sentence openers (Davis, 2003).

Existing Research on Regulation Support

Regulation Support in Writing

Important insights to regulation support can be drawn from research on writing. Similar to research on writing, learners in inquiry learning also take notes and protocol the stages of inquiry. Therefore, research on writing and inquiry learning often has the common goal of providing support for learners while they explain. Research on writing shows that supporting explanations by promoting specific processes leads to promising results. Scardamalia and Bereiter (1985) used specific prompts, called *procedural facilitation cues* while planning essays. These prompts aimed at stimulating self-questioning. Example prompts that were used during the planning phase included "Someone might think I am exaggerating, because…" or

"An important point I haven't considered is…" These prompts are more specific than explanation prompts because they target specific issues that are related to problems during composition. In comparison to explanation prompts, the prompts used by Scardamalia & Bereiter (1995) fulfill a more specific function than generic reflection. They promote the regulation of flow of thoughts by prompting specific processes that are needed to engage in composition successfully, e.g., considering multiple perspectives. Results showed that students who were using these prompts produced essays exhibiting more evidence of thought.

Berthold and colleagues (Berthold, Nückles, & Renkl, 2007) could impressively show that prompts can activate processes that lead to higher learning outcomes. The authors compared several prompt conditions during a writing activity, called cognitive prompts, metacognitive prompts, a mixed model called metacognitive and cognitive prompts, and a control group with no prompts. Cognitive prompts (e.g., "Which are the main points in your opinion?") aimed at triggering cognition, but metacognitive prompts (e.g., "Which points haven't I understood yet?)" aimed at triggering the regulation of cognition. Results show that prompts functioned as process activators (Reigeluth & Stein, 1983 in Berthold et al., 2007), because prompts resulted in the elicitation of metacognitive and cognitive statements. In addition, prompting also lead to higher learning outcomes in comparison to no prompting. However, if metacognitive prompts were provided alone without cognitive prompts, no effects on elicited statements and on learning outcome were found. In other words, metacognitive prompts did not lead to the activation of regulation processes if they were provided alone; they did so only in the mixed model. These findings imply that support of regulation processes via prompts should be accompanied by other kinds of support (Chapter 2.4.1) and that the combination of giving support and active knowledge construction needs to be well balanced.

Regulation Support in Inquiry

The following studies compare regulation support with explanation support or no support. Support refers to different ways of prompting, often called *cues*, hints, or reminders. Regulation support involves specific prompts aiming at regulating the flow of thought. Explanations support is a more generic form of prompting aiming at provoking thought and thus reflection.

King and Rosenshine (1993) investigated regulation support in a collaborative inquiry classroom setting. Fifth grade students were trained within their respective group to ask questions using different question stems. During the treatment, each condition received one of three cue card types including specific questions starting with “Why is … important?” or “What would happen, if…?” or generic questions starting with “Why…?” and “How…?” or to simply ask questions without additional guidance. Specific questions included structured question stems and generic questions were generic thought provoking questions. The authors claimed that cue cards with specific questions guide students in asking better questions and activating regulation processes such as the access of prior knowledge and monitoring. Results showed that students who used specific question stems outperformed students using generic question stems and students who asked questions without guidance. Thus, the comparison between prompts including generic and specific question stems could successfully show that specific instruction on how to execute processes (via regulation support) leads to better learning outcomes than generic question stems (via explanation support) that are merely prompting to explain.

Coleman (1998) has found similar results using *procedural prompts* in a collaborative inquiry classroom unit about photosynthesis. These are similar to procedural facilitation cues developed by Scardamalia and Bereiter (1985). The study compared students using procedural prompts with students who did not use procedural prompts but were encouraged to explain and discuss. Procedural prompts were for example: “How does your explanation compare with the scientific definition learning in class?”, or “Can you compare how you used to think about this with how you think about this now?” or “Explain why you believe your answer is correct or wrong”. These procedural prompts were specific, because they required the learner to focus on aspects, which need to be taken into account when developing advanced scientific explanations (e.g. contrasting differences between everyday explanations and scientific explanations). These prompts were of regulative nature, because they required the learner not only to explain but also to "justify, evaluate and to contrast their personal knowledge with scientific knowledge" (Coleman, 1998, p. 391). The prompts were provided as written questions or prompts on cue cards during a discussion or while explaining and students themselves decided when it was the best time to use one of the cue cards. Students in one learning unit (group consisting of three students) were instructed either to respond to the prompts individually or to discuss within the group over a period of several weeks. Results indicated that students receiving the prompting procedure outperformed those who did not receive the prompting procedure (but were encouraged to discuss and to develop explanations without the provision of the cue cards). Specifically, students receiving procedural prompts scored better on a knowledge posttest, generated explanations that were more advanced, and performed better in a concept-mapping post task. A qualitative analysis of the explanations and discussions indicated that the experimental group (utilizing procedural facilitation prompts) engaged in more situations of cognitive conflict than the control group. The experimental group receiving prompts was able to sustain longer discussions and to ask questions similar to those from the cue cards without using them at exactly that moment. In sum, the use of specific question stems or specific prompts was more beneficial than using generic questions ("please explain") or prompts to elicit explanations.

Prompts utilized in Lin and Lehman's study (1999) aimed at making learning processes explicit using prompts. University students learned about strategies for effective variable control in a simulation-based biology environment. Different prompts were utilized for that matter to compare effectiveness of prompt types. Students received either reason-justification prompts, rule-based prompts or emotion-focused prompts. *Reason-justification prompts* (e.g., "How are you deciding what to do next?") were directed towards triggering regulation processes such as planning, monitoring, evaluating and revising. Therefore, they can be classified as regulation prompts. *Rule-based prompts* were content-related and aimed at triggering explanations with respect to procedures and rules of the content domain (e.g., "What variables are you testing?"). *Emotion-focused prompts* (e.g., "How are you feeling right now?") included encouragement to monitor one's own emotional-motivational state. Prompts were provided throughout the problem-solving activity, first time before problems were identified, second time before running the experiments, and a third time after conclusions were drawn. Findings show that with respect to near transfer tasks no differences between groups were found. This can be partly explained by ceiling effects that were found with respect to near transfer items. With respect to far transfer items, the group receiving reason-justification prompts outperformed the control group and all other groups. Posterior qualitative analyses revealed that students in the reason-justification prompts group engaged more in regulation processes than the control group. For instance, individuals engaged more systematically in planning several steps ahead (e.g., “I will select a random sample of isopods, and then separate the variables etc…”). They engaged more in monitoring by keeping track of mistakes, judging own procedures, and evaluating their own learning (e.g., “I don’t know how I got these results”). An analysis of actions within the respective prompt groups revealed more systematic behavior of the reason-justification prompts group than the control group. In sum, reason-justification prompts were advantageous in comparison to other prompts and in comparison to no prompts at all, except for near transfer items.

Similarly, Davis and Linn (2000) compared effects of different types of prompts namely self-monitoring prompts and activity-related prompts. These prompts were delivered within a specific tool called *MILDRED* that was offered within the learning environment *KIE* (Linn, 1995). *MILDRED* (Bell & Davis, 2000) includes facilities for taking notes and providing questions, hints and prompts while doing so. *Self-monitoring prompts* aimed at encouraging reflection, specifically planning (e.g., “To do a good job on this project, we need to…”) and monitoring (“In thinking about how it all fits altogether, we’re confused about...”). *Activity-related prompts* were related to the activity itself (e.g., “The major claims in the article include...”). Results showed that students who received self-monitoring prompts developed better explanations. For instance, they included less descriptive explanations and more scientific content than the group receiving activity-related prompts.

Advantage and Disadvantages of Prompts

The studies above show that prompts have several advantages. Compared to training, prompts are economic when implemented in context of the learning activity itself. Recent developments in computer-based environments offer prompts in various formats. For instance, the studies by Lin and Lehman (1999) as well as Davis and Linn (2000) delivered prompts within the respective computer-based environments using computer-based prompts. Through prompting, a training can be reduced to an introduction with respect to the purpose of prompts or it can be replaced completely (Davis and Linn, 2000). This is an advantage in contrast to delivering prompts on cue cards (Coleman, 1998; King & Rosenshine, 1993), which requires a training of how to use the cue cards during the activity. The inclusion of training follows the assumption that learners have no or limited knowledge of regulation processes available. An availability deficiency cannot be overcome by prompts only. According to Veenman and colleagues (Veenman et al., 2005) however, even young learners have a pool of regulation processes at their disposal, but often regulation processes are not applied spontaneously due to a production deficiency. This production deficiency can be overcome by reminders in form of prompts.

However, the effectiveness of prompts to offer regulation support is not proven unequivocally. Davis (2003) assigned 178 students to either a directed prompt condition or a generic prompt condition. Students in both conditions worked in the inquiry environment *KIE* (Linn, 1995) to critically investigate scientific content via the internet. *Generic prompts* (e.g., "Right now, we're thinking…") aimed at promoting reflection and *directed prompts* (e.g., "To do a good job on this project, we need to…") aimed at regulation by giving suggestions what to think. Generic prompts can be also categorized as explanation support, and directed prompts can be categorized as regulation support. An analysis of responses showed that many students in the directed prompt condition were not encouraged to engage in reflection or regulation. Davis (2003) called this avoidance of prompts *no problem behavior*, because most students just tried to ignore the directed prompts. In contrast, she found out that in the generic prompts condition, the students showed less no problem behavior. As a result, findings with respect to performance during the activity also showed negative learning results related to the respective prompt condition. Davis (2003) identified several reasons why directed prompts did not trigger regulation as intended: If students are not able to understand the prompts correctly (e.g., because prompts are too complex), they respond with ignoring the prompts and engage in floundering behavior instead. In addition, if students are constantly reminded to check their understanding, they give up and avoid regulation.

Reasons for Heterogeneous Results

There are several reasons why prompts do not show positive effects across all studies. One reason concerns the heterogeneity of prompts that have been used. The prompts utilized in the studies above include domain-dependent information and guidance related to regulation processes. They all aim at triggering regulation processes but vary with respect to other aspects presented subsequently.

1. Prompts pursued different goals, because they emphasized different aspects of regulation processes. The regulation support included by King and Rosenshine (1993) was not solely related to regulation processes but also related to reflection. For instance, one of the prompts "Describe…" merely triggers reflection and does not aim at regulating the flow of thought. Prompts provided by Coleman (1998) aim at supporting evaluation, specifically emphasizing the relation between everyday knowledge and scientific knowledge ("How does your explanation compare with the scientific definition learning in class?") and consistency between both knowledge sources. Lin & Lehmann's (1998) prompts specifically aimed at planning, monitoring, evaluating, and revising one's own learning. Linn & Davis (2003) prompts aimed at supporting planning and monitoring.

2. The studies described above implemented prompts in different ways by delivering different formats of prompts in activities. King and Rosenshine (1993) and Coleman (1998) utilized cue cards to deliver prompts that were written on the cue cards. In

both studies, students in the prompting condition received an extensive training on how and when to use the cue cards. In addition, the teacher intervened if cue cards were not used for a long time. In case of Lin and Lehman's study (1999), the prompts were delivered individually to every learner within the computer-based simulation program that a student was working with. Prior to treatment, every student was told how to respond to the prompts within the respective prompting condition. The study by Davis and Linn (2003) used computer-based prompts as well; however, the students were not told on how to respond to prompts.

3. The studies also delivered prompts at different times during the activity, depending on when the activation of specific processes was needed. In the studies by King and Rosenshine (1993) and Coleman (1998), the delivery of prompts was affected by a teacher who delivered the prompts whenever it seemed to be appropriate. Hence, the timing of prompting varied. The studies that utilized computer-based prompts, delivered prompts at the same time for all prompting conditions (Davis, 2003; Lin & Lehman, 1999). Findings in Lin and Lehman's study (1999) revealed that students responded very differently to prompts at different stages during the activity. This suggests that the effectiveness of prompts varies with respect to the timing of the prompts.

In sum, prompts are effective but specific aspects need to be considered when designing prompts. These aspects concern the goal of prompting, the ways of prompting and the timing of prompting. Other inquiry studies that combined and compared regulation support with other types of support (e.g. with inquiry support) have also shown positive effects (Veenman et al., 1994; Zhang, Chen, Sun, & Reid, 2004).

Assessment of Prompting Effects

Only some of the studies described above analyzed the quality of the learning process by including an online assessment as a treatment check. Online assessment takes place in contrast to offline assessment during the task and it can be an important additional component to offline assessment in order to see whether interventions worked as intended, e.g., whether prompts elicited intended responses.

Online methods include observations, recall, log-file analysis, and eye-movement registration. Offline assessment takes place before and after the task and is usually administered via questionnaires. For economic reasons, offline assessment has been widely used (Veenman, 2005; Wirth, 2003). Yet, offline methods often do not correspond to findings from online assessment. Lin and Lehman (1999) conducted online assessment in two ways. They compared the different types of responses as part of a treatment check with respect to the prompt conditions. Response analysis revealed that each prompt type elicited intended statements with respect to processes. In addition, the students' actions were examined according to experimental conditions. Action analysis showed distinctive patterns between prompt conditions with respect to inquiry processes. Coleman (1998) only analyzed log-file excerpts. She found that in most cases prompts seem to function as intended.

Apart from the question whether prompts function as intended, another important aspect in prompt studies is to find out if learners reproduce the intended behavior even when prompts are not deployed anymore. The question is: Will learners, having received prompts during the treatment, also be able to engage in effective processes once the prompts are not present? Alternatively, will the absence of prompts at a later stage lead to a failure of triggering processes autonomously? King and Rosenshine (1993) included a transfer session in which students engaged in discussions as they did in earlier lessons, but during the transfer session students were not provided with cue cards (treatment). King and Rosenshine could show that students with guided cue cards still were able to ask questions with elaborated question stems. It must be noted, however, that all students also received training within the respective groups, which might have lead to the fact that students asked good questions even without the cue cards. Lin and Lehmann (1999) included similar and dissimilar problems within the performance assessment to show that learners benefitted from the prompts even in situations where the prompts were not provided. None of the studies included a test, which required the learners to repeat the tasks experienced during the treatment without the prompts or with a baseline prompting condition.

In sum, studies have been described that investigated different types of support: 1. Regulation support, which is specific support that aims at guiding the flow of thought, 2. Explanation support, which is generic support aiming at provoking thought and, 3. No support, providing no encouragement in terms of regulation or reflection. There is evidence that prompts, which specifically aim at triggering regulation processes, foster learning more than prompts which trigger reflection only.

Rules for Prompting Students During Inquiry

The previous chapter presented various ways to provide support during inquiry learning. The last sub-chapter focused on regulation support, which is often provided in form of prompts. This chapter will give special attention to support using prompts. The aim of this chapter will be to focus on rules for prompting specifically in the area of inquiry learning.

Goals of Prompting

Prompts have been found to be effective for stimulating specific processes that are important for learning (Pressley et al., 1992). In comparison to directive support such as training, prompting interventions presume that learners may have a production deficiency (Veenman, 2005), whereas training interventions assume an availability deficiency. Hence, prompts should be employed if the goal of the treatment is to activate processes learners have in principle available, but do not produce spontaneously.

Ways of Prompting

Prompts can be delivered by various sources. A teacher can offer prompts in form of verbal cues or cue cards during instruction. Prompts can be also provided by peer students (King & Rosenshine, 1993). Besides human prompting, recent efforts within the area of computer-based environment have shown that computer-based prompting is as effective as human prompting (Hausmann & Chi, 2002). Computer-based prompts can be presented as text-based prompts and as picture-based prompts, but text-based formats were found to be more successful than picture-based formats

(Reisslein, Atkinson, & Reisslein, 2004). Text-based prompts can come in different formats, for example as questions, sentence starters, hints, cues etc. Bell and Davis (2000) have found that for inquiry learning hints and sentence starters are most suitable. Hints can be used to make expert thinking visible, but sentence-starters can be used to make the learners' own thinking visible. The studies described in Chapter 2.4.2 have shown that prompts are effective if they are self-explanatory and do not lead to mental overload. Rosenshine and colleagues (Rosenshine, Meister, & Chapman, 1996) found in a meta-analysis that least effective prompts were also most mentally challenging for the learner.

Depending on the goals that prompts may have, the level of coercion should be decided on cautiously. Coercive prompts force the learner to draw attention to the information that it includes. In a computer-based environment, coercive prompts can be accomplished by pop-ups that interrupt the activity flow of the learner. In contrast, less coercive prompts allow the learner to continue focusing on the activity and allow skipping the information. These less coercive prompts can be implemented as messages, which appear in a corner of a workspace. Less coercive prompts can also be embedded via a link in the workspace, where learners can attend to them when it is needed. In inquiry learning, prompts can be provided to help learners to accomplish the inquiry task itself by supporting inquiry processes (e.g., running an experiment, making a prediction, or controlling variables). Inquiry processes, such as manipulating a variable, need to be accomplished by every learner to be able to proceed with a task. Therefore, to promote these activities, highly coercive prompts are suitable. Furthermore, prompts can be used to support regulation. Highly coercive prompts are not suitable for fostering regulation, because for some learners these prompts could lead to a reactant behavior based on too much coerciveness. For those learners regulation might require too much information processing. For other learners, attending to regulation prompts might be necessary to achieve a certain level of knowledge integration that allows the subject to, e.g., make inferences. In the case of regulation, prompts should be less coercive to allow for flexibility. Thus, the prompts can function as scaffolds (Chapter 2.4.1 for a description of what scaffolds are) that allow the learner to skip or follow a prompt depending on the learner's level of expertise, experience and mental effort (Vygotsky, 1978). Another approach to scaffolding is to use adaptive prompts. Prompts can be called adaptive if the information and format of the prompts is adapted to changing conditions (Leutner, 1995). Prompts can be adapted depending on previous employment of processes in earlier runs of an activity (Schwonke, Hauser, Nückles, & Renkl, 2006). Prompts can be also adapted over time by including a fading mechanism (Atkinson et al., 2003). Another approach is to conduct an online analysis of learners' explanations to provide an immediate adaptation of prompts based on the quality of explanations (Aleven & Koedinger, 2002).

Timing of Prompting

One big question within prompting research is when to provide support such as a prompt or a sentence opener. Prompts can be provided during different times of a learning sequence, e.g., during the knowledge acquisition phase and during a follow-up activity after the knowledge acquisition phase. Depending on the time when a prompt is provided, students rather use the information to adjust and improve the learning path that is ahead or reconsider and evaluate the learning path that just happened (Mathan & Koedinger, 2005). Hausmann and Chi (2002) conclude from their study of human and computer supported prompts that the timing of prompts is not important as long as there is enough opportunity to self-explain. These studies were conducted in the context of problem solving. One important aspect of timing is the time span in which prompts should be provided. Several insights can be gained from research within the context of writing, specifically from the research group around Renkl. According to Berthold and colleagues (Berthold et al., 2007), prompts focusing on aspects regulating cognition are not effective during a short time-span, e.g., just within one iteration of a writing activity. Therefore, prompts with respect to regulation should be given over a longer period. However, this may lead to an *overprompting* and thus to a detrimental effect of prompts on learning performance (Rosenshine et al., 1996). Little research has been conducted to investigate specific timing effects of prompts during inquiry learning. A pioneering study by Thillmann and colleagues (Thillmann, Künsting, Wirth, & Leutner, 2009) could show that prompts are more effective with respect to learning if they comply with the learner's regulation process. In other words, the effect of prompts varies if prompts are well adjusted to the learning process or not. Findings of her study suggest that the implementation of prompts should take into account the learning process through which a learner needs to go through.

In general, it can be assumed that prompts should be embedded within respective phases of inquiry to reinforce thinking processes related to the task. In addition, prompts addressing regulation processes should be included in several inquiry cycles to be effective.

Finally, it is important to note that prompts, even when they are designed carefully, can affect learners in different ways. One aspect that seems to have an impact on the effectiveness of prompts is the existing knowledge of the learner. If learners have limited knowledge about the processes that prompts are targeting, the prompts will be less effective (Veenman et al., 2005). If learners are novices in the task domain, they might not be able to compensate additional load that is established through the prompts (Bannert, 2004). Another important aspect that should be considered when designing prompts is the perceived usefulness of prompts (Berthold et al., 2007; King & Rosenshine, 1993). Especially when prompts are used within several inquiry cycles, learners should perceive prompts as useful.

Summary. The main aim of regulation support is to activate regulation processes, which is expected to facilitate formulating rich explanations that include scientific reasoning while engaging in a cycle of inquiry. Students can be prompted to give scientific explanations during inquiry learning. However, when they do not know how to regulate their thoughts successfully during explanations, their explanations will become superficial. This superficiality is characterized by minimal evidence of scientific reasoning. Specific prompts can be utilized to encourage students to refer to prior knowledge and to discover what is not known (Coleman, 1998). Furthermore, specific prompts can draw a students' attention to their own thinking processes and to understand the activity they are currently engaging in (Lin & Lehman, 1999). Therefore, specific types of prompts are needed in order to help learners regulating their flow of thought while formulating explanations during an inquiry cycle. Thus, regulation in inquiry learning has to deal, among others, with designing and conducting appropriate experiments in order to produce new information that can lead to scientific understanding. Therefore, regulation prompts should be related to explanations in specific phases of inquiry learning.

2.4.4 Limitations of Guidance

In a recent debate concerning learning and instruction, there has been a discussion between leading researchers (Hmelo-Silver et al., 2007; Kirschner, Sweller, & Clark, 2006; Kuhn, 2007) whether direct instruction (in contrast to minimal guidance) is effective. Although there seems to be an agreement that good instruction and good design is never without guidance, the question is how much guidance is too much and what forms of guidance are needed.

Veenman and colleagues (Veenman & Elshout, 1991) investigated the level of guidance by applying different levels of structuring. Completely learner-controlled environments might be not advantageous, but a highly structured environment might lead to reduced learning outcomes as well. Environments that require students to complete an inquiry cycle without additional guidance are especially difficult for learners that are unfamiliar with inquiry learning. Additional guidance to carry out inquiry processes seems to be important throughout all the phases of inquiry. Manlove and colleagues (Manlove et al., 2007) found that students who are provided with additional structure such as a predetermined goal structure performed better in developing a final model. On the other hand, too much guidance seems to be problematic as well. Veenman & Elshout (1991) found that a highly structured environment can lead to ignoring essential information, even if this information is necessary to complete the task successfully. Trafton and Trickett (2001) found that too much structure during a reflection activity can be disadvantageous. The authors investigated whether structured use of a notepad leads to higher performance gain than using the notepad alone. Four different modes of usage were compared: 1. a freeform notepad providing no structure, 2. a semistructured notepad (providing a list of all variables that can be manipulated and space for notes), 3. a full structured notepad (which included the structure of the second condition plus a menu that showed possible effects of each variable in the list) and, 4. no notepad (control group). Results showed that performance decreased with the amount of structure provided in the notepad, with exception of the control group that was outperformed by all other groups. In sum, to effectively engage learners in inquiry learning, a balance between providing activity structures (inquiry support), providing room for active knowledge construction (explanation support), and activating regulation processes (regulation support) is needed.

Recent approaches in science education have shown a development toward environments that strive away from the goal to relieve the learner from engaging in deep discovery during inquiry. There has been a shift towards developing computational tools that allow the learner to work together with the computer to investigate scientific phenomena (Dunbar & Fugelsang, 1995). These approaches see the learner as an active participant, with the learner constructing scientific knowledge instead of receiving a list of facts that can be learned and memorized. Computer-mediated environments provide tools that enable the learner to engage in a scientific investigation process instead of doing the investigation for him or her. To support this endeavor of working as a scientist, computer-based environments have integrated prompts, which are needed to engage in autonomous and meaningful inquiry activities. Rather than conducting quick and efficient experiments, these environments try to provide ways to think as a scientist. This includes the support of scientific reasoning in form of explanation-based activities by activating the learner to engage in regulation processes during a cycle of inquiry.

"I am going to increase the daylight successfully with one hour increase at a time."
(Student from Katedral School, Sweden)

3 Aims of the Thesis

Based on the general tenet that inquiry learning is beneficial for learning science (Chapter 2.2) and that learners face specific problems when engaging in inquiry learning (Chapter 2.3), three areas of support were identified and were described (Chapter 2.4). Taking into account the challenges related to inquiry learning, a learning environment was adapted (Chapter 5). In agreement with recent theoretical approaches to inquiry learning (Kuhn et al., 2000; Njoo & de Jong, 1993), the focus is on the analysis and support of regulation processes during inquiry learning. Specifically the need to support learners in regulating their flow of thoughts while engaging in inquiry has been identified as a crucial aspect (Chapter 2.4.3) to equip learners to engage in scientific reasoning. Prompts have been identified as appropriate means to support learners to engage in thought-provoking processes (reflection) and, more important, to regulate their flow of thoughts (regulation) while explaining.

A prerequisite for developing effective prompts (Chapter 2.4.3) is to analyze learners' explanations with respect to their engagement in regulation processes and their problems of developing scientific explanations during inquiry. A natural and highly motivating context is required to investigate learners' deliberate explanatory behavior during inquiry learning and to elicit rich explanations. In a first step, the following questions are investigated in an exploratory study to inform the development of support during inquiry learning:

1) What regulation processes do learners deliberately engage in when developing explanations and when do they take place?

2) What is the nature of explanation, when learners deliberately engage in inquiry learning?

3) Is there a relationship between statements indicating the presence of regulation and the quality of explanations?

In a second step, an experimental setting allows us to implement a support during inquiry learning focusing on the three aspects that have been identified: Inquiry, explanation and regulation. While inquiry support is believed to be necessary to enable learners to complete an inquiry cycle successfully, it needs to be investigated whether regulation support via specific prompts is more beneficial with respect to learning outcome than explanation support via generic prompts only. To be able to assess the benefits from a prompting support intervention, a knowledge test and a scheme for assessing the quality of explanations needs to be developed. In addition, a questionnaire needs to be developed to judge the learners' perception regarding the use of prompts. From these requirements, the following questions arise for a pilot experimental study:

1) Will learners who receive regulation prompts (in addition to explanation prompts) perform better in terms of *knowledge acquisition* and *explanation-application* than learners who receive explanation prompts only?

2) Do learners perceive prompts as useful?

A final step should include the replication of results of the previous study with a larger sample. In addition, it should be investigated how learners of both groups from the previous study (explanation support vs. regulation support) perform in contrast to a baseline group that only received minimal inquiry support and no explanation support at all. In addition to the knowledge test that has been evaluated in the pilot experimental study, an application test should be developed to measure effects of support on the quality of explanations while engaging in a cycle of inquiry. From that, the following questions arise for an experimental study:

3) Will learners who receive regulation prompts (in addition to explanation prompts) perform better in terms of knowledge acquisition and explanation-application than learners who receive explanation prompts only?

4) Will learners who receive regulation prompts (in addition to explanation prompts) perform better in terms of knowledge acquisition and explanation-application than learners who receive minimal inquiry support only (and no explanation support at all)?

Hypothesis: “At first it is doing good, but later it gets too much light and then it freaks out.”
Analysis/Results: (empty)
New Question: “What happens if we change the amount of water instead of the amount of CO_2?”

(Student from Katedral School, Sweden)

4 Exploratory Study

The goal of this first study was to investigate learners’ deliberate engagement in regulation processes during an inquiry cycle while articulating explanations. In addition, it was of interest to explore the students’ explanations with respect to nature and quality. The investigation of students’ regulation processes and explanations is necessary to identify possible problems that students might have and thus derive ideas for supporting learners with respect to the development of explanations during inquiry learning.

4.1 Aims of the Exploratory Study

Specific research questions were:

1) What regulation processes do learners deliberately engage in when developing explanations and when do they take place?

2) What kind of explanations do learners deliberately engage in inquiry learning?

4.2 Method

This study followed a non-experimental design, which aims at exploring the learners’ deliberate explanatory behavior while engaging in a cycle of inquiry. The goal of the study was to observe students in their deliberate engagement in explanation activities and their spontaneous use of regulation processes while articulating explanations. During all sessions, two instructors were present who organized the workshop and interacted with the students. The focus of this study was not on creating a controlled environment but on creating a setting that encourages learners to engage in deliberate verbalization during an inquiry cycle.

4.2.1 Participants and Design

Twenty-one students (13 males, 8 females; aged 14 and 15 years) from a secondary high school in Sweden participated in the study. They were enrolled in an intensive science course and were regarded as highly interested in science. The students were recommended and asked to participate by their teacher. Prior to the study, they attended a knowledge acquisition session that covered basic knowledge about photosynthesis.

4.2.2 Learning Environment and Procedure

The study took place in the informal setting of a science center in Sweden. The students were asked to participate in a three-day workshop about photosynthesis. Three environments were used: WISE (Linn & Slotta, 2000) was used in a knowledge acquisition session, BioBLAST (Ruberg & Baro, 1999) and the InquiryTool (Wichmann, Gottdenker, Jonassen, & Milrad, 2003) were used in a "performance session".

In the knowledge acquisition session, students used the Inquiry Learning Environment *WISE* (Linn & Slotta, 2000). An existing WISE project called "What makes plants grow" was authored to match the goals of the workshop. Students learned principles of photosynthesis and plant growth in the context of evidence-based activities. Students were allowed to work together while working with WISE. The knowledge acquisition session was necessary in order to ensure that students had some kind of existing understanding regarding the parameters that affect photosynthesis and the principles related. Thus, students were able to access knowledge acquired during the knowledge acquisition session while articulating explanations.

During the performance session, students used *BioBLAST* and the *InquiryTool*. BioBLAST (Ruberg & Baro, 1999) is specifically tailored to run experiments within the context of plant growth and advanced life support. BioBLAST is a simulation program that allows students to set conditions, run an experiment, collect and save data. It simulates a plant growth chamber in a laboratory on a lunar space station. BioBLAST consists of several sections including a glossary and an introduction text to Advanced Life Support. The main area offers various parameters (Table 3) that can be changed to optimize conditions for plants.

Table 3. Parameters of BioBLAST

Parameter in *BioBLAST*	**Example**
Type of Plant	Lettuce
Square Meters	100
First Planting Day	1
Harvest Cycle (Days)	28
Experiment Length (Days)	28
Carbon Dioxide Level	300ppm
Hours of Light	12h
Crop Type	1

Some of the parameters (First Planting Day, Harvest Cycle) are preset, depending on the plant type that is selected. Various research questions can be investigated including the effect of plant type, hours of sunlight and level of CO_2 that is provided for the plant. Experiment runs can be conducted after all experiment parameters are set. An analysis-and-results view shows the data resulting from one experiment run. Several experiment runs result in one data set. The analysis page provides information about single experiment runs. The result page offers information about all collected data in form of numbers with respect to biomass production, oxygen, and water that was produced. The experiment data can be saved as a .txt file on a local drive.

In addition, students used *InquiryTool* (Wichmann et al., 2003) in the performance session to analyze the experiment data. InquiryTool allows the learner to represent predictions as trend lines and to visualize data results from experiments. A *Note Feature* can be used to state the research question and to save written explanations and conclusions (Figure 12). The *Shape Picker* and the *Drawing Feature* allow visualizing graphs that represent a hypothesis. Students can display experiment results and overlay self-drawn trend lines with experiment data curves to make conclusions.

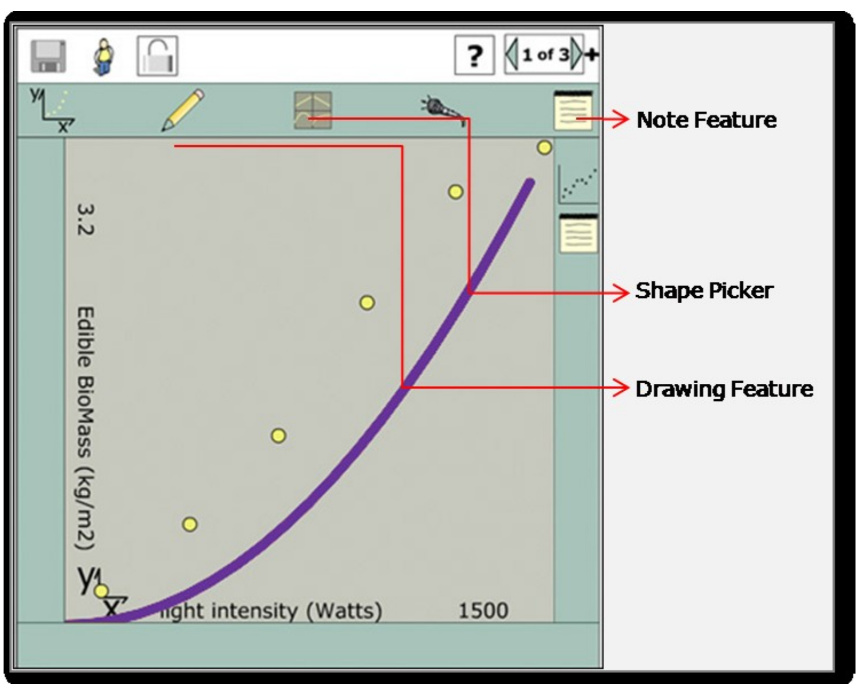

Figure 12. InquiryTool

The work with BioBLAST and InquiryTool lasted two hours and the students' artifacts were collected within an individual learning setting. Every student was asked to explain his or her predictions and results during the process using the InquiryTool's Note Feature. Students were allowed to ask questions to the instructors and the instructors helped out when it felt necessary. The artifacts created by the students were automatically logged and stored in a database. After an inquiry cycle, this database contained trend lines and verbal explanations including the formulation of hypotheses, conditions and a new research question.

4.2.3 Measures

Content Analysis

Students' explanations were analyzed according to the inductive qualitative content-analysis model by Mayring (2000). Category dimensions for regulation processes and quality of explanation were determined beforehand. These dimensions were used as criteria to select categories that lead to the final coding scheme. After half of the material was reviewed, a first version of the categories was developed. These categories were then applied to the rest of the content material. A final revision with slight changes was necessary after the whole material was reviewed. Subcategories were developed, which resulted from a reduction of the main categories to develop an overall coding scheme. Two researchers independently analyzed the data and developed the category system. Reliability was determined as level of agreement between the two raters, and the categories were discussed and revised until agreement was obtained.

Category System for Regulation Processes

The category system for regulation processes included three areas: Planning, monitoring and evaluation (see Table 4 for anchor examples for every category). A more elaborated description of these categories can be found in Chapter 2.2.3.

Planning in general includes working out next steps and allocating resources to outline next learning steps.

Monitoring refers to periodic self-testing of one's own understanding,

Evaluation refers to appraising the products and efficiency of one’s learning, which also includes evaluation of self and anticipated thinking

All statements were analyzed by checking the presence and non-presence of regulation statements in accordance to the three categories above. Unit of analysis was the explanation within a particular inquiry phase: hypothesis phase, experiment phase, results phase or new question phase. As a result, several regulation statements could be present for one student. For instance, if a student wrote explanations in every inquiry phase, the highest possible number of planning statements was four.

Table 4. Examples of Regulation Statements

Type of Regulation Statement	**Example**
Planning	*'I’ve decided to take two crops and to compare them and the amount of sunlight.”*
Monitoring	“*The crop’s edible biomass increased linear, the edible biomass increased in proportion with the hours of daylight (0.11 - 0.12/hour). That is quite logical because the more hours it gets the edible biomass it gets. But in the following diagram, I just marked every 4th hour. Because it was easier to fill in the results.*”
Evaluation	“*I had a good guess but it wasn’t correct.*” *“…if I would be able to do this experiment in one year, I think I get some other results because the plant would die.”*

Category System for Quality of Explanations

The following attributes were applied to code for quality of the explanations: Causality, complexity (reference to additional relevant variables) and consistency (consistency with biological principles and consistency with data). They are elaborated in more detail in Chapter 2.4.2.

Causality: Explanations are causal if they include causal relationships. These explanations include observations such as changes in plant growth. Causality does not imply that students refer to underlying biological principles. For example, the following explanation “Because I think the more daylight the crop gets the more edible biomass it will produce.” implies a correct causal relationship, but it does not reference underlying biological principles.

Complexity: If a student referred to one or more additional relevant variables besides the dependent and independent variable, the explanation was considered as complex. For example, in the statement “The amount of wind affects photosynthesis because wind leads to a higher evaporation of water.” “amount of wind” is considered as an additional variable that is important in the photosynthetic process.

Consistency: It was examined whether explanations were consistent with biological principles and consistent with data. An explanation is consistent with biological principles when correct principles of photosynthesis (e.g. Calvin cycle, light-dependent reaction) are referenced. An example of an explanation referencing a biological principle is: “The edible biomass will increase until it reaches saturation, because when the plant doesn’t need CO_2, the plants will close its stomata.”

All statements were analyzed by checking whether the described criteria were met or not. An explanation was determined to be of high quality, if all three criteria were met. Unit of analysis was again the explanation within a particular inquiry phase: hypothesis phase, experiment phase, results phase or new question phase.

4.3 Results

Results from the content analysis with respect to regulation processes indicate that students engaged little in planning and monitoring and mostly in evaluation (Appendix C). Planning statements included descriptions of the experiment design ("I am going to increase the daylight with one hour increase at a time."). Planning was done in the beginning of an experiment, whereas evaluation and monitoring were found during the analysis and results phase of the inquiry cycle. In addition, students who developed explanations of high quality also used more statements indicating regulation. Anticipated thinking, a subcategory of evaluation, was found towards the end of an inquiry cycle. Specifically, anticipated thinking was present in high quality explanations. Furthermore, students who formulated more high quality explanations also wrote more. This is in accordance with Chi and Bassok's (1989) findings of poor students generating less protocol lines than good students.

The following findings are based on the observations and interaction between student and instructors during the performance session. We repeatedly observed that students had difficulties during the hypothesis phase to predict their experiment results. Students showed an avoidance to draw as well as articulate their predictions without having empirical data supporting their prediction. When students were ready to draw a trend line representing the tendency of the expected experiment results, some mentioned that they were not able to do so, because they did not have any resulting data to rely on. In other words, students felt uncomfortable to engage in a practice of predicting. Several students complained that an exact hypothesis was not possible using the drawing tool and that they felt uncomfortable to draw an inaccurate trend line.

4.4 Discussion and Implication for the Following Studies

The results indicated that students deliberately engaged much less in planning and monitoring than in evaluation. This is in line with findings by Manlove & Lazonder (2004) who investigated students' verbalizations with respect to presence of regulation statements. Their analysis of students' chat messages revealed that students did engage in some planning, but that this planning behavior was not effective, because it was lacking a systematic method including goal setting.

With respect to observations made by the instructors during the performance session, it is difficult to interpret results because observations are only based on singular instances. A generalization is therefore not possible. It was observed that students avoided articulating their predictions without having empirical data backing up their explanations. The following reasons come to mind that trigger this kind of avoidance: One explanation could be that students are rather trained in empirical thinking instead of developing hypotheses. Traditional instruction often does not include the task of developing hypotheses (Germann, Haskins, & Auls, 1996). Another reason could be that students wanted to avoid inaccurate predictions in order to avoid the feeling of failure. This phenomenon has been called *fear-of-rejection* by van Joolingen and de Jong (1993). The latter reason could be supported by the fact that most students understood after the first experiments that making predictions without data was part of the task. The first reason upholds when analyzing the written explanations: In the initial inquiry cycles, students' explanations were rather descriptive, lacking causal relationships and biological principles. Evidence for causality was either superficial or not found at all. It seemed that direct instruction and practice to articulate scientific explanations might have been helpful to improve the quality of written explanations. One of the observations made when students were initially faced with the challenge of writing sound explanations was that students wrote very superficial explanations. Common statements were for example: "…because it is that way" or "I just know it". After some experience, many students were able to formulate statements that were based on data results. For example, common explanations were similar to the following statement: “The Biomass increases, because the plants are growing”. The engagement in complex and consistent explanations was only achieved when students had had some experience with writing explanations. Especially, encouragements from the instructors that were provided when students requested help, seemed to enhance the formulation of hypotheses (i.e., “Remember what you learned earlier about photosynthesis. Can you try to explain it by taking into account what you learned before?”). These insights suggest that regulative processes might need to be activated by an external facility. Inquiry learning environments should foresee an interface that allows engaging in several inquiry cycles so that students can practice the articulation of explanations during several inquiry cycles. Moreover, students should not only be encouraged to explain but also students should be provided with additional help on how to explain.

"I'd like to try this in reality. Computers are strange machines...."

(Student from Teknikum School, Sweden)

5 Learning Environment

This chapter describes the modeling environment that was used for conducting the research in this dissertation. First, the instructional approach is presented on which the adaptation of the existing learning environment FreeStyler is based on. The instructional approach is followed by the description of the topic that was chosen for this research. Finally, the learning environment is described and its appropriation to fit the needs to this research.

5.1 Instructional Approach: Reflective Prediction Cycle

The following instructional approach was developed based on the theoretical assumptions of inquiry learning (Chapter 2.2.1) advocated by White and Fredriksen (1998). The inquiry processes are based on a model of scientific inquiry, which result in an inquiry cycle. This inquiry cycle consists of inquiry phases that can be revisited iteratively or in cycles. During the learning process, the inquiry phases are made explicit to the students. In White and Fredriksen's *Inquiry Cycle* the inquiry phases are relatively simple to counteracting the idea that learning science is "only accessible to an elite subset of the population" (White & Frederiksen, 1998, p. 5). In the present instructional approach called *Reflective Prediction Cycle* (Wichmann et al., 2003), this idea of providing a simple inquiry cycle is adopted, but the inquiry phases were slightly modified to emphasize the cyclic nature of inquiry learning (Figure 13). The Reflective Prediction Cycle consists of five phases starting with an Orientation phase, continuing with a Hypothesis phase, an Experiment phase, an Analysis/Results phase, and ending with New-Question Phase.

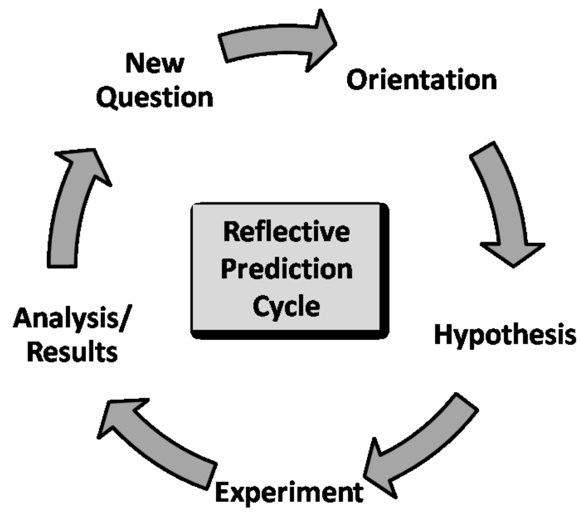

Figure 13. Reflective Prediction Cycle

5.2 Topic: Plants in Space

The topic of *advanced life support* is a challenging and motivating context for students to investigate the subject of photosynthesis. While photosynthesis seems to be a rather dry topic of learning in the science classroom, students are challenged when plant growth is presented in the more exciting context of *Life in Space*. Advanced life support focuses on problems such as “How can we feed 100 people on a remote space station?” In this context, the understanding of photosynthetic processes becomes relevant because it is necessary to optimize conditions for plants and humans successfully in a closed-loop system. The investigation of photosynthesis has been widely used (e.g., Coleman, 1998) as a basis for research on students’ explanations. It turned out to be an excellent topic for studying scientific reasoning processes, because students hold various misconceptions on photosynthetic processes. For example, a common misconception is that students perceive soil as being the main food resource for plants. In addition, according to Bell (1985), the role of nutrients is very commonly confused. The Reflective Prediction Cycle provides many opportunities to challenge these misconceptions.

5.3 FreeStyler

In the instructional approach, students follow an adapted inquiry cycle previously described as Reflective Prediction Cycle. This approach was realized in the learning environment *FreeStyler*, which is a powerful modeling software that combines the use of various visual languages with rich annotation options (Hoppe & Gassner, 2002). *FreeStyler* is not related to a specific subject, it therefore provides the freedom to be used for various topics, not only photosynthesis. *FreeStyler* supports many scenarios besides the inquiry scenario that is described in this dissertation (Wichmann, Kuhn, & Hoppe, 2006). The software provides modeling tools ranging from qualitative to operational modeling, which are accessible as plug-ins. The flexibility of combining these plug-ins and use them on the same workspace allows the learner to switch between modeling tasks. This allows the learner a high degree of freedom when it comes to making decisions during a scientific investigation. The modeling plug-ins can be used in combination with a drawing feature to realize a wide range of scenarios.

An adaptation of the *FreeStyler* environment was necessary to offer the kind of support that has been described in Chapter 2.4. The UML activity diagram below (Figure 14) captures the activities in an inquiry cycle as actions and the products (e.g. explanations, experiment data) as objects.

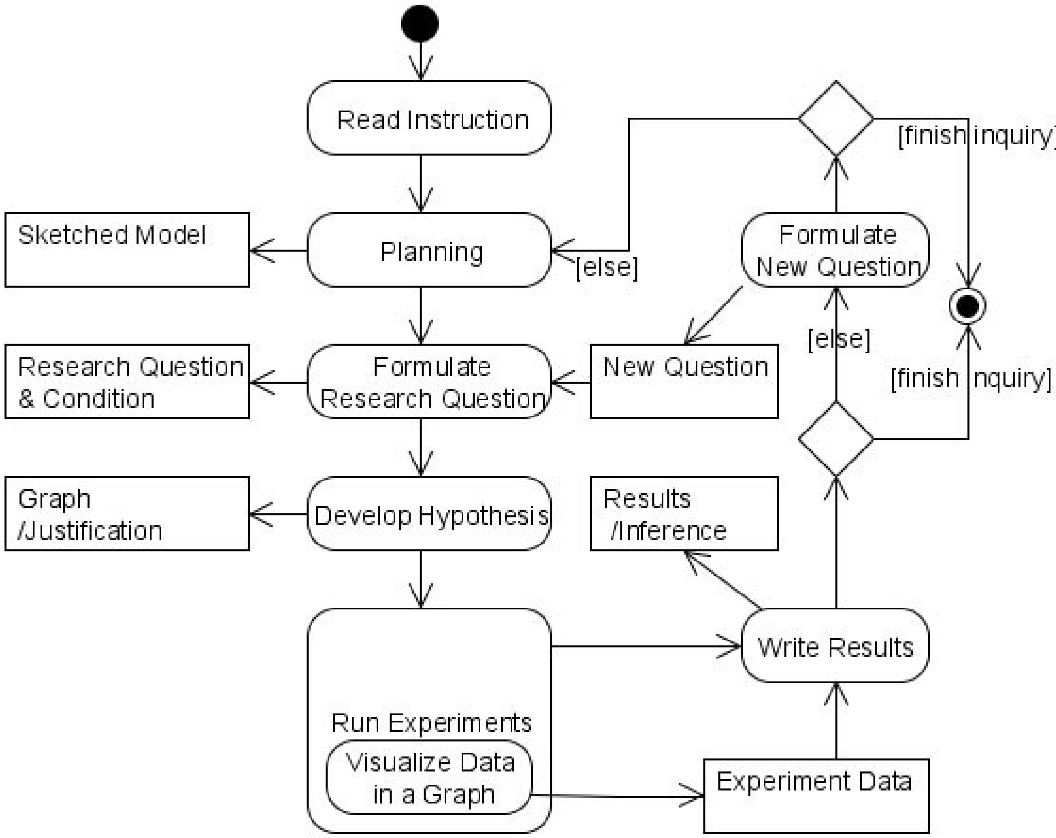

Figure 14. UML Diagram of the Inquiry Cycle in FreeStyler

For the provision of basic inquiry support in form of an activity structure, a tabbed interface was developed. Similar to the tabbed interface in *Inquiry Island* (Eslinger et al., 2008; White et al., 2002), the *FreeStyler* interface includes the phases of inquiry in a procedural manner to make the inquiry learning activity more manageable and to avoid getting lost (Chapter 2.4.1). Besides this procedural aspect, the tabbed interface offers also flexibility, because it allows the learner to switch back and forth between inquiry phases. Instead of following a rigid script, FreeStyler tabs encourage learner control. For advanced inquiry support, different *FreeStyler* plug-ins were adapted to provide support for specific tasks during an inquiry phase. In addition, different types of prompts (pop-ups, embedded prompts) were used to, e.g., provide guidance during the hypothesis phase. Explanation support and regulation support is realized via different prompts that are displayed on the *FreeStyler* workspace.

5.3.1 FreeStyler Plug-Ins Used in the Experimental Studies

Feedback plug-in. FreeStyler's Feedback plug-in consists of a modeling space, which allows learners to sketch a model (Chapter 2.4.1). Modeling by using the Feedback plug-in, allows learners to represent their existing conceptions about variables in a qualitative model (Löhner et al., 2005; Safayeni, Derbentseva, & Canas, 2005). The Feedback plug-in uses "+" and "-", which is the main convention of causal loop diagrams to represent causal relationships (Figure 15). If a "+" is selected to determine the relationship, a positive influence is predicted towards the variable that the arrow is pointing at. If a "-" is added to describe the relationship between two variables, a negative influence is predicted influencing the target variable.

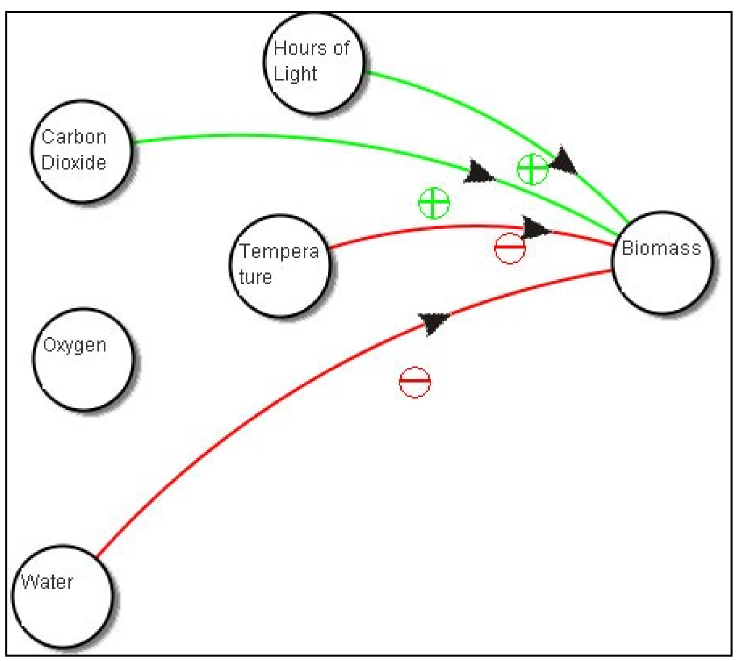

Figure 15. Screenshot of FreeStyler's Feedback Plug-in (Basic Mode)

The Feedback plug-in was redesigned for this study to enable more in-depth representations of the learners' knowledge. Besides a revision of the graphical interface, the plug-in was expanded, so that not only a simple dichotomous relationship (basic mode) between variables can be determined but also more complex relationships (advanced mode). Using the Feedback plug-in in a basic mode included only dichotomous labeling of the relationships. It allowed the learner to only determine whether two variables have a positive (+) or a negative relationship (-). Using the feedback plug-in in advanced mode offers the learner multiple labels to describe the relationship (Figure 16). The labels are accessible from a hover menu, and the learner needs to select the most appropriate relation among several relations. The labels in advanced mode are displayed as graphs including a positive increasing linear graph (If A increases then B increases too), a negative decreasing linear graph (If A increases then B decreases), a balancing graph (there is no relationship between these variables) etc.

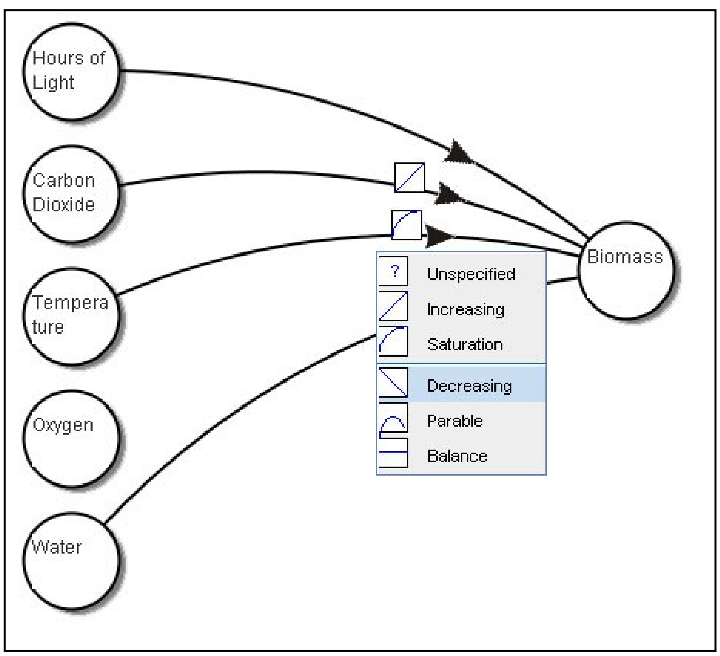

Figure 16. Screenshot of FreeStyler's Feedback Plug-in (Advanced Mode)

Function Plug-in. FreeStyler's Function plug-in was needed because the experimental data was produced outside of FreeStyler, using the Simulation program *BioBLAST* (Ruberg & Baro, 1999). The Function plug-in offers an import mechanism that easily loads and displays data within a graph. The import option was specifically developed for the studies conducted in the context of this dissertation. The *BioBLAST* import option allows selecting *.txt files that include data produced from *BioBLAST* experiment runs. A drop-down menu facilitates the selection of variables that can serve as dependent variable or as independent variable. The number of variables from which the learner can choose is limited to one dependent variable (biomass) and two independent variables (carbon dioxide and hours of light). Once the variables that match the ongoing experiment have been selected, the data is plotted as a data curve and displayed in a table below the graph (Figure 17). Besides Feedback and Function plug-in, different types of notes for typing and displaying text have been used. Furthermore, the drawing feature was available during the hypothesis phase to draw a prediction graph.

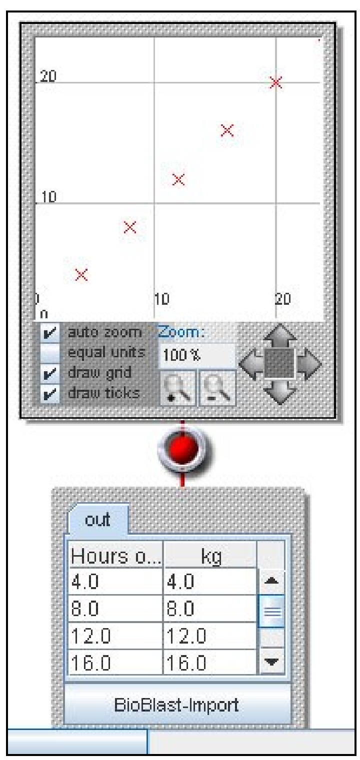

Figure 17. Function Plug-in

5.3.2 Basic Inquiry Version

FreeStyler was set up with pre-loaded tabs (Figure 18) according to the phases of the Reflective Prediction Cycle. Each tab is related to a specific phase of the inquiry cycle, starting with a *Plan tab* and ending with a New-Question tab. As such, the tabs provide basic inquiry support to engage sequentially in all phases of an inquiry cycle.

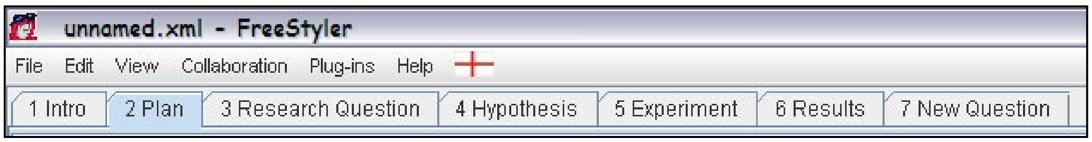

Figure 18. Tabbed Interface of FreeStyler

Orientation Phase: For the Orientation phase, two tabs are offered: the plan tab and the Research Question Tab. The Plan tab provides a modeling workspace that facilitates representing relevant variables in a causal-loop diagram (Löhner et al., 2005; Safayeni et al., 2005). In the basic mode of the modeling workspace, students assign dichotomous (positive or negative) relationships between relevant variables representing their existing conceptions about variables in a qualitative model. Using the Research Question tab, students can state their research question and conditions that are important for the experiment in a text field.

Hypothesis Phase: In the Hypothesis tab, students can represent their prediction for the experiment in a graph. Students use the *FreeStyler* drawing feature to represent the relationship between the independent and the dependent variable.

Experiment Phase: The Experimentation tab is related to the data collection phase of an inquiry cycle. The experiment is conducted outside the *FreeStyler* software, and the data are imported using the *FreeStyler function plug-in*. The import option allows learner to view the experiment data as a graph and compare it to the prediction made earlier. It assists the learner in selecting the independent variable and the dependent variable of the experiment. Once the learner has selected these variables, the imported data will be displayed in a graph.

Analysis/Results Phase: The Results tab is related to the analysis and results phase of an inquiry cycle; here students can write about the outcomes of their experiments in a notepad.

New Question Phase: The New Question tab is related to the end of the analysis and results phase of an inquiry cycle; here students can write a follow-up research question in a note pad. This is the last phase of the given inquiry cycle and leads over to the first phase of the next inquiry cycle.

Minimal support was provided via simple instructional prompts in form of pop-ups (e.g., “Go to the next step ‘Hypothesis’!”) that were placed between the inquiry phases. In sum, the Basic Version included the tabbed *FreeStyler* interface outlining the phases of an inquiry cycle, the basic version of the modeling workspace as a tool for the orientation phase, and simple instructional prompts.

5.3.3 Advanced Inquiry Version

The Advanced Version provided advanced inquiry support in addition to basic inquiry support described above. This included additional inquiry prompts, (“What is your dependent variable?”) and the advanced mode of the modeling workspace being used in the Plan tab of the orientation phase. In an advanced mode of the modeling workspace, students can select various types of graphs (linear, quadratic, exponential etc.) that represent the relationship between variables. This advanced mode facilitates a more precise representation than the basic version (Joolingen van, 2004). The advanced mode of the modeling workspace was chosen to offer a more precise way for students to represent their understanding that the basic mode. It allows students to determine the precise relation between variables concerning the specific form of the relationship between variables (vs. determining only whether there is a relationship or not). Besides the additional inquiry prompts and the advanced modeling workspace in the orientation phase, the same interface was offered as in the Basic Version including note pads, the drawing features etc.

5.3.4 Inquiry Support Using IMS/LD

Previous research (de Jong & Joolingen van, 1998) suggests that learners tend to skip essential phases of an inquiry cycle and just run the experiments. Structuring the inquiry process might help learners to keep track of their learning progress. To lay out a road map of inquiry should be therefore of value for the learner. A structure can be mapped onto a learning environment by providing a script. Recent developments in CSCL research (Kobbe et al., 2007) suggest that scripts can support the learner by providing an activity structure (Chapter 2.4.1).

The scripting approach used in this study is implemented using the IMS/LD. IMS/LD (Koper & Tattersall, 2005) is a formal language for defining learning scenarios, which focuses on the representation on learning processes. The language is defined as an XML notation and it uses a theater play as metaphor to define roles, activities, the environment, and resources. The learning process is represented as a theater play and learning sequences are represented as acts. Different roles can be taken on by those who take part in activities that are conducted in an environment. Resources are represented as requisites. IMS/LD distinguishes three levels A, B and C, starting out with the first one, A, becoming more complex in Level B and most complex in level C. Level A contains the core parts for activities along with the roles definition. The following core elements are provided to make up a unit of learning: method, play, act, role, role-part, learning activity, support activity, and environment. Level B provides important elements to control and adapt the learning process to the learner including properties and conditions. Level C provides notifications and allows triggering activities in response to events during the learning process (e.g. completing an activity). The level architecture of IMS/LD provides potential for adapting a learning process. In contrast to other approaches to learning design such as e.g. LAMS (Yan, Yang, Yang, Liu, & Huang, 2008) that can only be connected to particular learning environments, IMS/LD is flexible with respect to technology integration. IMS/LD was utilized to represent the inquiry script in this study for several reasons. IMS/LD scripts are automatically executable with the learning support environment (LSE). In addition, the script can be re-used within other learning environments. The following section will describe in more detail the technical implementation of the IMS/LD inquiry script used in this study and possible options for script re-use (Figure 19).

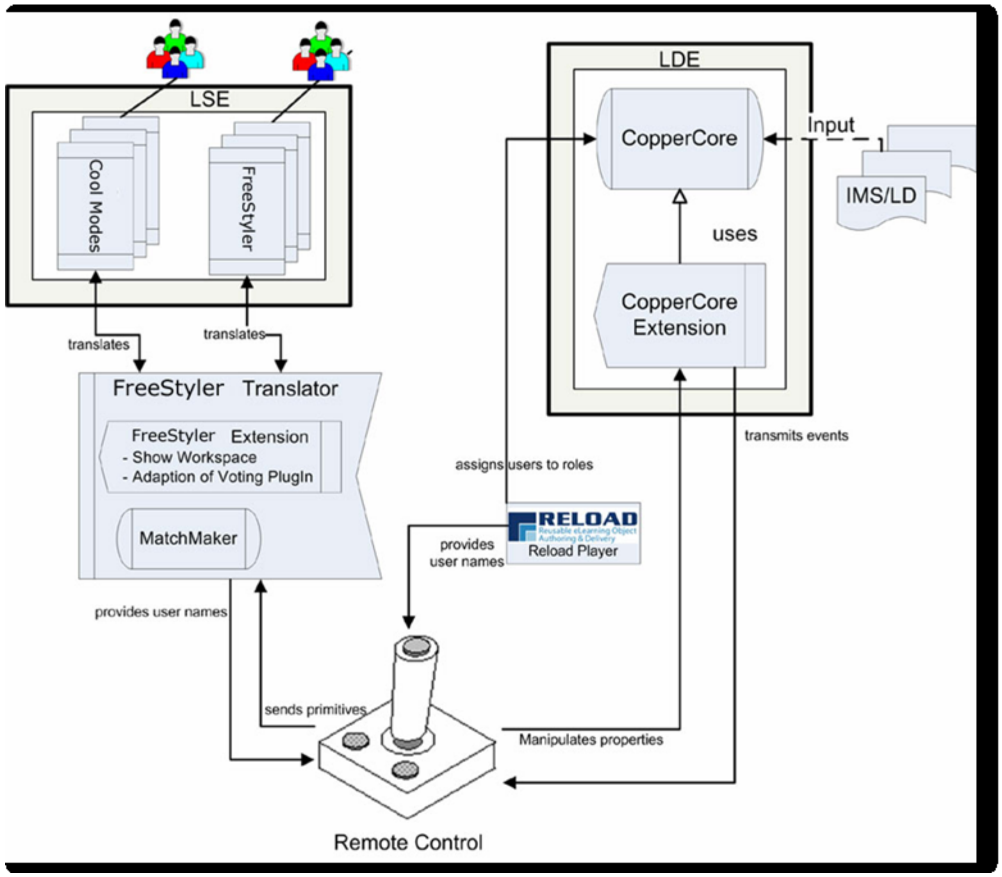

Figure 19. IMS/LD-based control of a LSE (Harrer, Malzahn, & Wichmann, 2008)

Copper Core is an open source program that is written to interpret IMS/LD documents. It is intended for web-based applications; therefore, we needed to add a copper core extension to send commands/primitives to the LSE, which in this case is *FreeStyler*. LSE we call any kind of learning environment that is Java-based. Other examples of LSE’s are CoolModes (Pinkwart, 2005), *CoLab* (de Jong et al., 2002) and *SAIL* (SAIL is the next generation of the *WISE* environment: Slotta & Linn, 2009). The Remote Control (Harrer, Malzahn, & Wichmann, 2008) is a program intended to remotely control any type of LSE. It is supposed to be a generic tool usable with all kinds of LSE's. Therefore, it speaks a generic language comparable to Esperanto. A translator is needed to translate it to the individual languages of the LSE's. The command send out by *Copper Core* could be „add new page“, which in

FreeStyler would translate into „*New workspace tab*" or in SAIL, it would translate in a *New hint* or *New looping activity*. The *Reload Player* is needed to start the activity. It assigns the individual users and runs which will then be matched in the *Remote Control* with users of the *LSE*. In *FreeStyler*, for example, when a user clicks on a prompt, „I finished drawing my prediction" primitives are sent to the *Copper Core* engine, which changes the state and sends out the new command to for example prompt the student to formulate a hypothesis.

Macro and Micro-level structure of the IMS/LD inquiry script. The *IMS/LD* inquiry script structures the inquiry activity in *FreeStyler* on two levels, a macro-level and a micro-level. On a macro-level, basic inquiry support is provided by structuring the sequence of the inquiry phases and determining the workflow. Thus, the macro structure guides the student through the experimentation process providing several phases of inquiry, such as the creation of research question, stating a hypothesis, experimentation, etc. Every phase of the inquiry cycle is represented as a tab respectively in the *FreeStyler* environment. Figure 20 shows Research Question as active tab. The tabs in *FreeStyler* are generated as a pre-existing guide. On a micro level, advanced inquiry support is provided. Here, the IMS/LD script generates prompts at run-time that give support during specific tasks of the experimentation process. Three different formats of prompts exist: 1. Inquiry prompts, which, e.g., request to state specific conditions of the experiment. 2. Explanation and Regulation prompts, which, e.g., request to explain and 3. Instructional prompts (e.g., "Please go to the next inquiry phase") that facilitate the transition between phases of inquiry. For each of the tasks different types of prompts are used to enforce different levels of coercion (Dillenbourg, 2002). For inquiry prompts, an embedded format is used; they are viewable from the moment, a learner starts an inquiry. Explanation and Regulation prompts, however, will be generated at run-time and appear once a specific task is completed. For instructional prompts, pop-ups are used, which are the most coercive format of prompt. Pop-ups interrupt the flow of the activity and require the learner to respond by pressing OK.

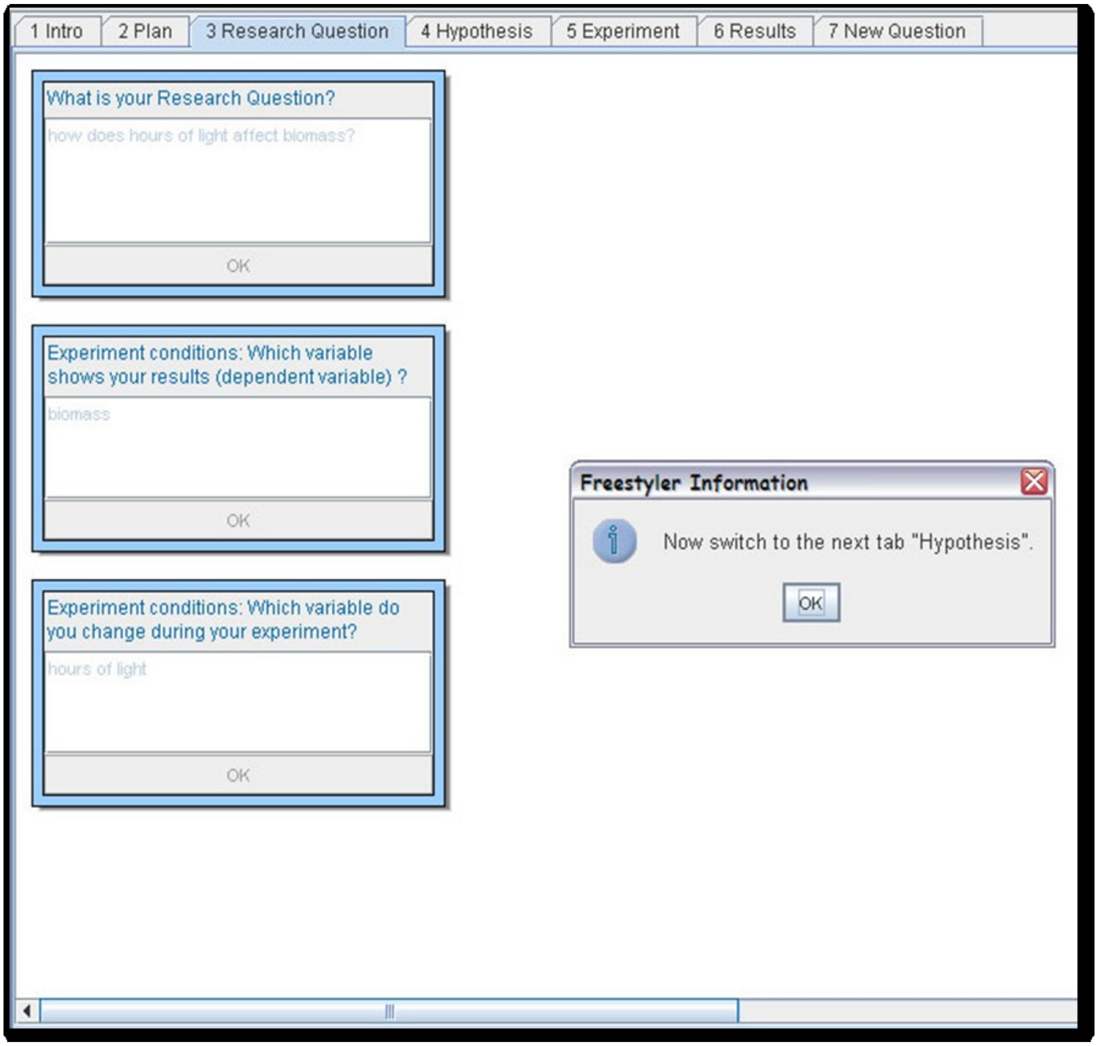

Figure 20. Inquiry Prompts and Instructional Prompts in FreeStyler

Hypothesis: „Das Ergebnis wird sich von meinem letzten Ergebnis unterscheiden, weil jetzt nur die Lichtdauer wichtig ist. Kohlenstoff Dioxid und andere Faktoren werden nicht berücksichtigt.“ Ich glaube diese Ergebnisse spiegeln insofern korrekte Daten wider, weil ich 6 Runs gemacht habe und ich so ziemlich genau entnehmen kann wie der Graph verläuft.“
Analysis/Results: „Ich habe erwartet, dass dies passieren würde, da ich mir nicht vorstellen kann, dass ab einer bestimmen Menge CO_2 die Biomasse steigen kann. Ich konnte mir nicht vorstellen, dass bei einer Überdosis die Biomasse weiter ansteigt.“
New Question: „Ungeklärt ist, wie der Biomassengehalt mit der Wasserzufuhr zusammenhängt.

(Student from Elsa–Brändström School, Germany)

6 Pilot Study

The goal of this study was to investigate the effect of regulation support via prompts in a computer-based inquiry learning setting. The specific regulation processes to be invoked by regulation prompts were identified based on findings from the exploratory study described in Chapter 4. The prompts were inspired by inquiry behavior and high-quality self-explanations of expert self-explainers observed in that study. Because of the problems learners face while developing explanations (Chapter 2.3.2), including the lack of regulation processes (Chapter 2.3.3), it seems necessary to offer support. Prompts seem to be the most adequate format (Chapter 2.4.3) to activate thought provoking processes and to help learners to regulate their flow of thought.

From a methodological perspective, the goal of this study was to trial the *FreeStyler* environment using IMS/LD scripts in a classroom environment to see whether the software is suitable to conduct larger classroom studies. In addition, the goal was to optimize the evaluation instruments, a content knowledge test and a questionnaire assessing perceived usefulness.

6.1 Questions and Hypotheses

The central question in this study was whether regulation support in form of regulation prompts leads to deeper understanding than explanation prompts only. One assumption was that students develop better explanations if supported via regulation prompts. This assumption seemed likely, based on the findings of other studies in the area of inquiry learning (Chapter 2.4.3), which showed that prompts can trigger intended processes. This was based on the general assumption that learners generally suffer from a production deficiency, but not from an availability deficiency (Chapter 2.3.3). Furthermore, it was expected that students receiving regulation support instead of explanation support not only explain better but also learn more. This assumption was based on findings that developing explanations within an inquiry cycle is an important but challenging endeavor (Chapter 2.3.2), which requires learners to engage in regulation processes. As learners don’t engage in regulation processes spontaneously (Chapter 2.3.3), appropriate support in form of prompts is needed (Chapter 2.4.3). Another question was whether prompts deployed within the inquiry cycle were regarded as useful. As described in Chapter 2.4.3 perceived usefulness is an important factor that should be taken into account.

In sum, the focus of the present study is on regulation support to be provided by prompting. The following hypotheses were tested:

H1: Students receiving regulation support in form of prompts will outperform students receiving explanation prompts.

H1.1: Students receiving regulation support in form of prompts will formulate better explanations than students receiving explanation prompts.

H 2: Students will perceive the learning environment and prompts as useful.

6.2 Method

6.2.1 Participants

Twenty students from a Gymnasium participated in the study. All students were in sixth grade and between 15 and 16 years old. Forty percent of the participants were female and 60% were male. Students had little prior knowledge in photosynthesis, as it was not part of the curriculum in their prior school year. Participants were matched based on pretest scores and then randomly assigned. Ten students were assigned to the regulation group and ten students were assigned to the explanation group.

6.2.2 Design

The study followed a one-factorial design with two different learning conditions, comparing the effect of regulation prompts (in addition to explanation prompts) with the effect of explanation prompts (Table 5). Groups in both learning conditions, called regulation group and explanation group, worked with the advanced version of the *FreeStyler* environment.

Table 5. Types of Support by Treatment Group

Regulation Group	**Explanation Group**
Regulation Prompts	
Explanation Prompts	Explanation Prompts
Advanced Inquiry Support	Advanced Inquiry Support

The explanation group received explanation support. Explanation support included explanation prompts ("Please explain!"). The prompts were placed at three points in the sequence of an inquiry cycle: (1) prompting an explanation of the hypothesis in the hypothesis phase, (2) prompting explanations while analyzing the results of an experiment in the analysis and results phase, and (3) explaining the next research question at the end of the analysis and results phase.

The regulation group received explanation support and regulation support. Regulation support included regulation prompts (often in form of sentence openers) and hints (Table 6). During the hypothesis phase, regulation prompts encouraged testing one's own understanding and comparing the hypothesis to previously gained experience. During the analysis/results phase, regulation prompts were related to appraising findings by prompting awareness of cognitive conflicts, re-checking the inquiry process, and paying further attention to one's own understanding. During the new question phase, regulation prompts were provided supporting the transition of understanding gained during the ongoing cycle and making predictions that may affect the next cycle.

Table 6. Regulation Prompts

Inquiry Cycle Tab	**Regulation Prompt**
Hypothesis:	Why does the independent variable affect the results in the way you predicted? Please remember what you learned before about photosynthesis
	Do you think that the results will differ in comparison to your last experiment? Why?
Experiment	Compare your result graph with your hypothesis. Are they different from each other?
Results:	Did you expect these results? There may be aspects that you didn't take into account.
	Do the results make sense to you?
New Question:	Which experiment could you do next? This experiment should be runable with the tools available.

All groups were allowed to make notes throughout the inquiry cycle on a note pad, provided on the *FreeStyler* workspace tabs.

6.2.3 Learning Environments

Three different learning environments were used within this study. For the knowledge acquisition session, the inquiry learning environment *WISE* (Linn & Slotta, 2000) was adopted to provide learners with a knowledge base about photosynthesis. For that purpose, the existing *WISE* project "What makes plants grow?" was translated into German (project name: "Wachsen Pflanzen auch auf dem Mars?") and tailored to the objectives that were relevant for this study. For the performance session, the *FreeStyler* environment (Chapter 5.3) in which the phases of the inquiry cycle were represented (Chapter 5.1), was used. While *FreeStyler* served as a tool to follow the steps of inquiry, students used *BioBLAST* (Ruberg & Baro, 1999) to run the experiments and to get the data. As a model-based simulation, *BioBLAST* allows students to alter variables related to plant growth easily, to make experiment runs, and to save the experiment data.

6.2.4 Procedure

The study was carried out at the Elsa-Brändström-Gymnasium in Oberhausen, Germany. All sessions took place in a school computer lab, which was equipped with 30 PCs. The study was planned to take place over three sessions with one week in between two sessions (Table 7). During the last session, half of the class was missing. It took place at one of the last school days in June before the school year 2007 ended. Hence, we had to repeat the third session day for the missing students after summer vacation, in August 2007. Students participated at each session for two hours, respectively. In the beginning of the first session, called knowledge acquisition session, students filled in the regulation test. After that, students worked in pairs at the computer, taking an introduction in photosynthesis and advanced life support using the inquiry environment *WISE* (Linn & Slotta, 2000). Students worked with *WISE* for one session day. The *WISE* material covered specific aspects that are relevant in the context of advanced life support. Every aspect was organized in distinct activities. Once an activity was finished, the next step of a new activity could be selected. An activity usually consisted of information (called “evidence” in *WISE*) in form of text passages, pictures, or animations related to a specific aspect of plant growth. The students could follow customized hints and questions related to the information provided in the main browser window. For instance, students read van Helmont’s text (http://en.wikipedia.org/wiki/Jan_Baptist_van_Helmont) to determine where plants get their mass from and discussed the purpose of soil by following *WISE* hints and answering questions posed by the *WISE* software. A voting activity was included to encourage students to share their different views on the purpose of soil. Other activities introduced the factors relevant for plant growth including the light-dependent and light-independent reactions and the role of nutrients. The closing activity familiarized students with the specific approach of plant growth investigated for space missions, called hydroponics. The session with *WISE* served as a knowledge acquisition session to get familiar with the subject matter of photosynthesis.

Table 7. Sessions During Pilot Study

	N = 20
Knowledge Acquisition Session	*WISE* →Pretest Knowledge
Software Training Session	Training *BioBLAST*, Demo and Training *FreeStyler*
Treatment Session	Inquiry Cycles 1 and 2 → Posttest Knowledge → Questionnaire Perceived Use

After the *WISE* project was finished, a pretest was administered. The second session was a training session that introduced the students to the software *FreeStyler* and *BioBLAST*, which were both used for the inquiry cycles. The software was first introduced to the students via a data projector. Students had time to familiarize themselves, with each student working on one computer individually. Every student logged in with his or her respective login name and password. A link to *FreeStyler* and *BioBLAST* was provided on each desktop to start the programs easily. Then, each student worked in a training cycle using the software *FreeStyler* to follow the inquiry cycle and using the Software *BioBLAST* to conduct experiment runs. During the treatment session, each student worked separately on one computer. Students followed two inquiry cycles investigating a new question about plant growth optimization in every cycle. Both inquiry cycles were recorded via log files for post analysis. After every cycle, a final pop-up reminded every student to save the data at a specific location on the desktop. This saving procedure was closely monitored by two researchers. The first cycle investigated the effects of light hours on biomass production. In the second cycle, students concentrated on changing the amount of carbon dioxide and on observing its effect on plant growth. At the end of the treatment session, every student received a questionnaire assessing perceived use of the *FreeStyler* environment and the prompts. Subsequently, the post knowledge test was administered.

6.2.5 Measures

Knowledge Pretest

The pretest administered before the treatment was identical to the content knowledge test administered afterwards.

Knowledge Posttest

A content related knowledge test consisting of 20 items was developed concerning the topic "Plants in Space". The test was administered as a pretest before conducting the inquiry cycles. The same test was administered again right after the inquiry cycles to assess knowledge gain (Appendix A). The test consisted of two parts. The first part included 16 declarative multiple-choice and open-answer items concerning photosynthesis and inquiry. For example, one photosynthesis multiple-choice item was:

> The photosynthetic process removes_______ from the environment.
>
> a) Soil,
>
> b) Sugar,
>
> c) Oxygen,
>
> d) Carbon Dioxide

An example of an inquiry item is:

> Whenever scientists carefully measure any quantity many times, they expect that...
>
> a) All of the measurements will be exactly the same.
>
> b) Only two of the measurements will be exactly the same.
>
> c) All but one of the measurements will be exactly the same.
>
> d) Most of the measurements will be close but not exactly the same.

Some of the items were self-developed and some were taken from TIMSS (The TIMSS International Study Center, 1995). The second part of the test contained two inquiry tasks tapping procedural knowledge. Every inquiry task was a combination of a multiple-choice item and an open question provided in a 2-step way. The first part required to select a correct prediction graph (multiple-choice) that corresponded to the experiment setup that was described, for example, "Pick a shape that represents best the effect of exceeding CO_2 on biomass production. Note that the plant will be sufficiently supplied with all other components (water, nutrients etc.)." The second part required to formulate an explanation concerning the prediction. The procedural knowledge part was developed in close relation to the actual activity that students did during the inquiry cycles. Multiple-choice items were scored with respect to whether the correct item was selected or not. The open answers were scored by defining indicators beforehand. If a specific indicator or a set of indicators was present, the item was scored as correct.

Content Analysis

For the analysis of explanations, we only chose one aspect to categorize the quality of explanation, as the focus of the pilot test was to develop the test instruments. Based on the qualitative content-analysis approach that was used in the exploratory study, two raters analyzed the explanations based on whether they were consistent with principles of plant biology or not. Consistent explanations received one point, and explanations that that were not consistent with principles received zero points. Students who did not write any explanation at all received zero points as well. An explanation consistent with principles was for example, “Glucose is produced in the Calvin Cycle during the dark-reaction”. An explanation that was not consistent with principles was for example, “If light goes up, then biomass goes up, too”. Because this was a very simple category for analysis and a small sample, both raters agreed on all explanations. Even though students were prompted for explanations during four inquiry phases, only explanations of the hypothesis and the analysis/results phase were used to analyze the quality of explanations. Explanations during the experiment phase were not included in the analysis, because students wrote (if at all) descriptive explanations only. Explanations during the new-question phase included only descriptive explanations related to the next experiment and a new research question.

Perceived Use Questionnaire

The focus in this study was the utilization of prompts within an inquiry cycle. Besides the effectiveness with respect to learning outcome, it was also important whether students perceived prompts as useful or not (Berthold et al., 2007). Seven items were developed to measure perceived use of prompts that are implemented in *FreeStyler*. Perceived use was measured on a 5-point Likert scale measuring the level of agreement with every item, with 1 corresponding to low agreement (“I do not agree at all”) and 5 corresponding to high agreement (“I completely agree”). The items focused on aspects of use. One question was, for example, whether the prompts were helpful during the inquiry cycle. An inverted item asked whether the prompts were distracting during the inquiry cycle.

6.3 Results

6.3.1 Knowledge Pretest

All differences were analyzed with non-parametric tests because of the small sample size (n = 20). Because of a matched random assignment, Mann-Whitney test revealed no differences between regulation group (M = 7.1, SD = 1.3) and explanation group (M = 7.2, SD = 1.1), Mann-Whitney U = 36.0, p = .46.

6.3.2 Knowledge Posttest

Before looking at the effect of support that was provided during the treatment, general learning gain through the inquiry activity itself was measured, so that it was possible to measure the effect of prompts later on. Students answered more items correctly after (M = .76, SD = .11) the treatment in comparison to before the treatment (M = .57, SD = .12). This results in a statistical difference (z = -3.48, p = .001), which was analyzed by means of a two-sided Wilcoxon signed rank test. With respect to group differences, we found no significant (Mann-Whitney U = 46.5, p = .78) differences between the explanation group (M = .78, SD = .07) and the regulation group (M = .74, SD = 0.14) in the posttest. Missing group differences can be explained by the strong ceiling effects that were found with respect to the declarative items and the very low overall reliability of the posttest (Cronbach's Alpha = .163).

Only four items were included in the procedural part of the knowledge test. The procedural part required to perform tasks similar to tasks that needed to be performed in an inquiry cycle. Two items were multiple-choice items, which had strong ceiling effects and which were answered equally well by both groups. The two remaining items were open-format items, in which the students were asked to explain their decisions. The open-format items in the procedural part were related to the multiple-choice part of that item. Hence, if a student answered the multiple-choice item correctly, the open answer of the corresponding open-format item was often correct, too. If this was not the case, students didn't provide any explanation at all, even if they provided a correct multiple-choice answer of the first part. More students in the regulation group provided correct explanations in comparison to students in the explanation group (Mann-Whitney $U = 23.0$, $p = .024$).

6.3.3 Content Analysis

Explanations from *FreeStyler* log-files were analyzed with respect to quality of explanations. The quality of explanations was determined by checking whether explanations consistently referenced biological principles or not (Chapter 2.4.2). Due to the few data points available, we will not analyze the data statistically. Descriptively, there is some evidence that students in the regulation groups had an advantage over students in the explanation group. During the hypothesis and analysis/results phase, mainly descriptive explanations were found in both groups (Table 8 and Table 9). Group differences were only found in the analysis/results phase. During the hypothesis phase, no group differences were found because very few students (20 %) wrote explanations referencing principles. During the analysis/results phase, students wrote more explanations referencing principles (45 %) in comparison to the hypothesis phase (20 %). During the analysis/results phase, differences were found between groups. Students in the regulation group wrote more explanations referencing principles (60 %) than students in the explanation group (30 %).

Table 8. Hypothesis phase - Explanations Referencing Principles

	Group	
	Regulation Group	**Explanation Group**
No explanation	10%	30%
Descriptive	70%	50%
Concept Referencing	20%	20%
Total	100%	100%

Table 9. Analysis/Results phase - Explanations Referencing Principles

	Group	
	Regulation Group	**Explanation Group**
No explanation	20%	40%
Descriptive	20%	30%
Concept Referencing	60%	30%
Total	100%	100%

6.3.4 Perceived Use Questionnaire

Two students had to leave before filling in the *perceived use questionnaire*, which results in a reduced number of 18. Perceived use was assessed using seven self-developed items. Reliability of the questionnaire was .73, which is considered acceptable. As it was expected, no significant differences were found between treatment groups. Students rated all positive items higher than 3 (on a 5-item Likert scale), and they rated all inverted items (orange bars: pu4, pu56 pu7) lower than 3 (Figure 21). An example for an inverted item is: “Receiving the prompts was quite exhausting.” Specifically item pu5 (“The prompts helped me to go through the inquiry step by step”) was rated higher than 4 (M = 4.06, SD = .87). In other words, all students agreed that prompts were useful during the inquiry cycle

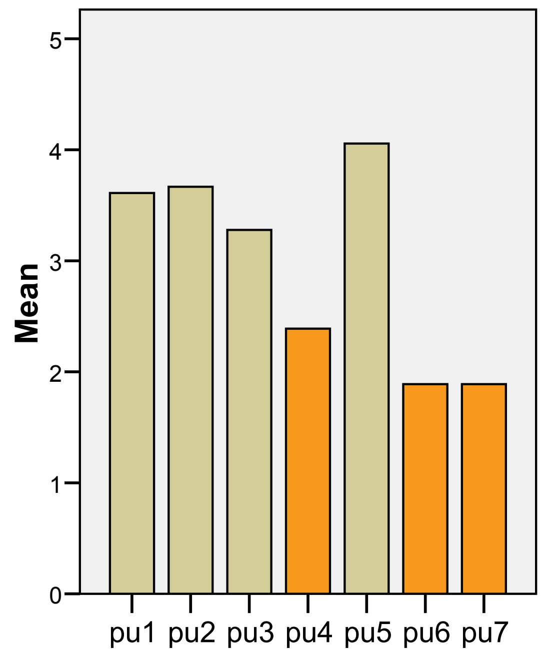

Figure 21. Perceived Use of Prompts

6.4 Discussion

Overall, a knowledge test has been developed and tested. Based on the categories developed in the exploratory study, one criterion for assessing the quality of explanation has been evaluated in order to be able to determine immediate effects of prompts on students' behavior.

Although the findings of the knowledge test showed partial effects, an adaptation of the instrument for the main study is necessary. Especially the declarative part of the knowledge test was not effective for measuring group effects, because of ceiling effects and very low internal consistency. The procedural part was appropriate, as it did not reveal ceiling effects and group differences were found for the open items. For the adaptation of the instrument, the declarative part of the knowledge test needs to be reduced to items that show discriminatory power. In addition, the procedural part needs to be expanded by additional transfer items.

With respect to the content analysis, results show that students who wrote better explanations - as a direct response to prompting -. However, one question that has not been tackled is whether students are be able to benefit from regulation prompts during the inquiry cycle even if prompts are taken away. In other words, do students benefit from regulation prompts sustainably? Therefore, the main study needs to include an additional inquiry cycle that offers no differences in treatment. Thus, a sustained effect of prompts can be investigated.

With respect to the treatment, students responded that they perceived prompts as helpful during the inquiry and not too mentally exhausting. Especially, regulation prompts seemed to be beneficial; yet the effects were not as strong as expected. One reason could be that the prompts to explain were not as explicit in the regulation group as in the explanation group. The goal however was to include regulation prompts as an additional support to explanation prompts. In the future study, the encouragement to explain has to be made more explicit in the regulation group.

Hypotheses: *”*In think, both experiments reach their maximum photosynthetic potential when they start getting excess CO_2. Since the one has 19 more hours of sunlight, it has more potential. Sorry for my sucky graph but I REALLY suck at drawing. ;-)”
Analysis/Results: *”*Both reached their photosynthetic potential probably around 1200 ppm and the biomass production remained the same after that. The plants can only take in a certain amount of CO_2. The amount of sunlight each day adds enzymes to carry energy that is used to carry out photosynthesis. So, when you have 19 extra hours to use photosynthesis you get more biomass. Rubisco is used to make the reaction and can only make so many reactions per second.”
New Question: “Why is Rubisco SO slow AND stupid?”

(Student from Katedral School, Sweden)

7 Main Study

The goal of this study is to replicate the experimental pilot study and to expand it by one additional condition. Furthermore, a dependent variable was added to be able to determine the effect of regulation support on explanation performance, specifically focusing on the aspect of scientific reasoning. Based on the learner’s problems of developing explanations that include scientific reasoning, specifically with respect to the difficulties of successful knowledge coordination (Chapter 2.3.2), learners need to be supported to engage in regulation processes. Because we assessed the immediate effect of regulation support on learners’ explanations in the pilot study, we now were interested in whether students in the regulation group benefitted sustainably from the regulation support.

7.1 Questions and Hypotheses

Although inquiry tasks are effective means for learning science, basic inquiry support often results in insufficient learning performance (Kirschner et al., 2006; Mayer, 2004). In order to increase learning performance, learners should receive advanced types of inquiry support. The theoretical assumption of the present study is that successful inquiry learning requires students to engage in scientific reasoning in order to develop scientific understanding. Scientific reasoning may be induced by prompting students for explanations on what they are doing in the phases of an inquiry cycle. However, in order to produce strong scientific explanations leading to deep scientific understanding, students need to be prompted for appropriately regulating their flow of thought when developing explanations. Otherwise, without prompting for regulation, one accepts the risk that students do not engage in scientific reasoning and hence fail to gain deep understanding.

Thus, the focus of the present study is on *explanation support* and *regulation support* to be provided by prompting. We expect that explanation prompts combined with regulation prompts will equip students better for successful learning than basic inquiry support only. We believe also that explanation prompts combined with regulation prompts will equip students better for successful learning than providing explanation prompts only. However, it is an open question whether explanation prompts alone will be sufficient to result in better learning performance than basic inquiry support only.

In the present study, students' explanation activities are manipulated by prompting them to activate regulation processes.

H1: Students who receive regulation prompts will perform better in terms of knowledge acquisition than students receiving explanation prompts.

H2: Students who receive regulation prompts will perform better in terms of explanation-application than students receiving explanation prompts.

H3: Students who receive regulation prompts will perform better in terms of knowledge acquisition than students receiving basic inquiry support only.

H4: Students who receive regulation prompts will perform better in terms of explanation-application than students receiving basic inquiry support only.

7.2 Method

From a methodological point of view, this study aimed at implementing the instruments that have been tested and adapted in the previous study. Moreover, the design is extended by adding a third condition.

7.2.1 Participants

Seventy-nine students (53 female, 24 male) from three science classes of Swedish higher track secondary education schools participated in the study. The students were between 15 and 16 years old. All classes took science as an emphasis of study, and all science classes were taught in English. For balancing purposes, the participants were clustered based on a pretest and were within each cluster, randomly assigned to one of three learning conditions. As a result, the regulation group consisted of n = 28, the explanation group consisted of n = 29 and n = 22 students participated in the basic inquiry group. Due to various reasons (computer network problems, logging failures, illness) the number of participants varied across analyses and across conditions. One major reason was that all files that were generated throughout the treatment had to be saved on a shared network folder, because files on the local drives were immediately deleted in case of a computer restart or a student logging out. Even though students were explicitly prompted to save the data on a shared folder, some files got lost anyway.

7.2.2 Design

The study followed a one-factorial three-group design with three learning conditions in which the amount of inquiry support was stepwise increased (Table 10) from basic inquiry support over explanation support to regulation support, each type of support being added to the previous one.

Table 10. Types of Support by Treatment Group

Basic Inquiry Group	**Explanation Group**	**Regulation Group**
		Regulation Prompts
	Explanation Prompts	Explanation Prompts
Basic Inquiry Support	Advanced Inquiry Support	Advanced Inquiry Support

The *basic inquiry group* (n = 22) served as the control group of the study and received basic inquiry support via the basic inquiry version of *FreeStyler*. The basic inquiry version included the tabbed *FreeStyler* interface outlining the phases of an inquiry cycle, the basic mode of the modeling workspace as a tool for the orientation phase, and simple instructional prompts (e.g., "Go to the next step 'Hypothesis'!") between the phases. This setup corresponds to the phases of inquiry as they are typically supported in inquiry-learning environments (Löhner et al., 2005).

The *explanation group* received advanced inquiry support and explanation support. Advanced inquiry support was offered through the advanced version of *FreeStyler*. In addition, the students received explanation support in form of prompts ("Please explain!") at three points during the inquiry cycle, during the hypothesis phase, during the analysis/results phase and during the new question phase.

The *regulation group* received advanced inquiry support, explanation support and regulation support. Regulation support included prompts and hints that were placed next to explanation prompts.

The regulation prompts used in this study were the same as in the pilot study, except some small modification. These modifications were an improvement to the last version and included:

1. The regulation prompts were placed next to the explanation prompts to make explicit that regulation prompts are an add-one to explanation prompts. It was made sure that in all three phases in which regulation processes were elicited that also explanations in general were elicited. In the former version used in the pilot study,

explanation prompts in the regulation group were found to be not explicit enough. In Table 11, the difference between prompts used in the pilot study and prompts used here has been made explicit by writing the modifications in bold type. Sentence-openers have been added in addition to the prompts and explicit explanation prompts have been included. With respect to regulation processes, the prompts stayed the same.

2. Regulation and explanation prompts were reduced to the following inquiry phases: hypothesis phase, analysis/results phase and new-question phase. The prompts that were included in the experiment phase in the pilot-study were now moved to the analysis/results phase.

Table 11. Regulation Prompts

Inquiry Cycle Tabs	**Regulation Prompt**
Hypothesis:	[Hint: **Please explain in detail** why the independent variable affects the results in the way you predicted. Please remember what you learned before about photosynthesis **and write it down**.]
	Do you think that the results will differ in comparison to your last experiment? Why? ***The results will be different to my last experiment, because…***
Results:	Compare your result graph with your hypothesis. Are they different from each other?
	Did you expect these results? **Please explain your results in detail.** ***The results are expected / not expected because…*** [Hint: There may be aspects that you didn't take into account]
	Do the results make sense to you? ***I think these results are somehow correct, because…***

New Question:	**Please think about which questions have not been answered yet and** which experiment you could do next… [Hint: This experiment should be testable with the tools available.]

7.2.3 Procedure

The study took place in classroom lab settings of two Swedish schools with a shared computer network. Each class participated in the study consisting of two sessions, and each session lasted for three hours (Table 12).

Table 12. Sessions During Main Study

	N = 79
Day 1	WISE *Plants in Space* →Pretest Knowledge
Day 2	Training *BioBLAST*, Demo and Training *FreeStyler*
Day 2	Inquiry Cycle 1 and 2 Inquiry Cycle 3 (Knowledge Application Test) → Posttest Knowledge

In the first session, all students participated in a three hours photosynthesis introduction lesson. Students worked in groups with the inquiry environment *WISE* (Linn & Slotta, 2000), focusing on the overall theme of advanced life support and on optimal conditions for plant growth. Subsequently, a knowledge pretest was administered. In the second session, five days later, students started working with the modeling software *FreeStyler* and the simulation program *BioBLAST* according to the experimental learning condition they were allocated. While *BioBLAST*'s functionality could be easily grasped by students via discovery, we prepared a small demonstration to introduce working with *FreeStyler*.

During the treatment, each student worked separately on one computer. Links to *BioBLAST* and *FreeStyler* were provided on every workspace as well as three folders labeled Experiment 1, 2 and 3 that were used to save the experiment data collected during *BioBLAST* experiment runs. Students followed two simulated inquiry cycles investigating a new question about plant growth optimization in every cycle. Cycle I investigated the effects of light hours on biomass production. Cycle II concentrated on changing the amount of carbon dioxide and observing its effect on plant growth. After that, students were required to apply what they had learned before in a final cycle III by focusing on the interaction of light hours and carbon dioxide. Students were reminded by a *FreeStyler* pop-up after every cycle to save the data on a specific location on the network-shared server. The saving procedure was closely monitored by two researchers. The knowledge posttest was administered right after the students finished their final inquiry cycle.

7.2.4 Measures

Knowledge Pretest

A pretest that was identical to the post knowledge test, examined students' knowledge after the photosynthesis introduction session. The pretest scores were used to match the three treatment groups.

Time-on-Task

Time on task was not controlled, but logged (in seconds) for post-experimental inspection. We recorded time on task for every inquiry cycle by logging the time from starting the script until saving it on a shared folder (which was done by every student after finishing each inquiry cycle). Some logging data got lost or was unusable. Especially in the first inquiry cycle, we had in several cases two log files per student because of program failures. These students restarted the program and continued. Time-on-task scores of these students were not used in further analyses.

Knowledge Posttest

The knowledge posttest (Appendix A) consisted of two parts just as the knowledge test in the pilot study. The first part included declarative multiple-choice items concerning photosynthesis and inquiry. All open items of the declarative part that were included in the pilot study were removed. Instead, more emphasis was taken on the second part of the test, assessing procedural knowledge. The procedural part was expanded by adding two additional tasks, each of them consisting of two items. Both new tasks were similar to the existing tasks of the procedural part with respect to item construction. They consisted of two items: 1. a multiple-choice item that required to choose one out of three prediction graphs corresponding to an experiment set-up that was described, and 2. an open-format item that included a request to explain the graph of choice in the multiple-choice item. Both items required to exercise the performance of the inquiry cycle within different experiment set-ups, e.g., investigating the effect of CO_2.

Explanation-Application Test

Whereas the three treatment groups received different support in inquiry cycles I and II, inquiry cycle III was intended to function as an application test in which learners were expected to show what they had learned in the two cycles before (Table 13). Because we were interested to check for the quality of explanations in this test cycle, all students of all treatment groups were provided with that version of the three *FreeStyler* software versions in which they were allowed and encouraged to give explanations. That is, all students received the software version with advanced inquiry support and explanation prompts in this test cycle. This allowed us to test whether students of the regulation group were willing and able to apply what they had learned in inquiry cycles I and II (that is, engaging in scientific reasoning) without any longer being prompted to do so in cycle III. Furthermore, this test design allowed us to test whether students of the explanation group, who had articulated explanations in cycles I and II before, produced better scientific reasoning than students of the basic inquiry group who had not articulated explanations before.

Table 13. Inquiry Cycles

Inquiry Cycle	**Support**
Inquiry Cycle I: Light	Different for Treatment Groups
Inquiry Cycle II: CO_2	Different for Treatment Groups
Inquiry cycle III: Interaction of Light and CO_2 (Explanation-Application Test Cycle)	Same for All Treatment Groups

The explanation-application test (inquiry cycle III) required students to conduct an experiment investigating the interaction of the two independent variables of inquiry cycles I and II. While students were already familiar with the effects of both variables independently, the explanation-application test consisted of a completely new experimental task focusing on interaction effects.

All explanations that were written during the explanation-application test (inquiry cycle III) were saved in the XML-format of *FreeStyler*. The explanations were automatically extracted from the XML-Files and saved in a RTF-file that also included the IDs, the inquiry phases, and the conditions. The RTF-files could be easily imported in the text analysis software MAXQDA (http://www.maxqda.com). The categories were automatically displayed in the coding system. For the coding, the category indicating the conditions was removed. Two independent raters coded the quality of explanations, in terms of presence (1 point) or absence (0 points) of scientific reasoning. This was done for explanations concerning the hypothesis and explanations concerning analyzing the results, respectively. Explanations concerning the next research question were not analyzed because these explanations did not have a specific focus on scientific reasoning. During the coding procedure, explanations containing scientific reasoning were identified using a filtering method. First, if a student described descriptive, observational changes only (e.g., “The graph goes up”), then he or she received 0 points, and these explanations were taken out of the further analysis. Second, if a student identified and determined a correct relationship of two relevant independent variables, this was coded as scientific reasoning (1 point). Identifying and determining the relationships included describing the non-linear interaction of two independent variables on the dependent variable. Explanations, however, were not coded as scientific reasoning (0 points), if the determined relationships between variables were incorrect (e.g., “Biomass goes down, when CO_2 increases”). In order to get an explanation-application test score, the two codings of the hypothesis explanations as well as the two codings of the results explanations were averaged each, and the averaged codings were then summed up. The two averaged codings correlated at r = .40.

7.3 Results

7.3.1 Reliability

All offline assessment instruments were piloted in the Pilot study, reliability was measured using Cronbach’s Alpha (Table 14). Reliability of the knowledge pretest was a bit lower than acceptable and for the post-knowledge test reliability was excellent (Nunnaly, 1978).

Table 14. Reliabilities of Instruments

Instrument	**Reliability (Cronbach’s Alpha)**	**Number of Items**
Knowledge Pretest	.65	16
Knowledge Posttest	.77	16

For the online assessment instrument, called the explanation-application test, inter-rater reliability was determined using Cohen’s Kappa. The coefficient determined the level of agreement between two independent raters determining the quality of students' explanations. Cohen's kappa was .77 concerning explanations written during the hypothesis phase and .89 concerning explanations written during the results phase, suggesting substantial agreement with respect to coding categories.

7.3.2 Time on Task

Across treatment groups, students spent on average 25 minutes to run an inquiry cycle (Table 15). Most time was spent on cycle I (33:19, min:sec) in comparison to cycle II (22:27, min:sec). ANOVA revealed no differences between treatment groups for both cycles, $F(2, 42) < 1$, $MSE = 37471.28$, and $F(2, 42) < 1$, $MSE = 65045.21$, respectively. Hence, time-on-task spent in each treatment group was similar for both inquiry cycles. During the explanation-application test (Inquiry cycle III, that all groups conducted with the same type of prompts), the basic inquiry group spent descriptively less time on the cycle than the two experimental groups. However, the differences between groups were not significant, $F(2,42) = 2.41$, $MSE = 93550.12$, $p = .102$.

Table 15. Descriptive Statistics for Time on Task (Minutes: Seconds)

	Treatment Group*	M	SD
Inquiry Cycle I	Regulation	33:78	15:62
	Explanation	33:34	12:59
	Basic Inquiry	32:04	12:68
	Total	33:19	13:54
Inquiry Cycle II	Regulation	20:57	06:56
	Explanation	20:99	06:26
	Basic Inquiry	18:74	07:00
	Total	20.27	06:47
Inquiry Cycle III	Regulation	19:47	05:46
(Explanation-	Explanation	18:88	05:16
Application Test)	Basic Inquiry	15:34	04:32
	Total	18:23	05:26

* N(Regulation Group) = 17,

N(Explanation Group) = 17,

N(Basic Inquiry Group) = 11.

7.3.3 Learning Gain

A precondition for measuring prompting effects is to measure learning gain through the inquiry learning activities. Overall, we found a significant difference between knowledge pretest and posttest measures (Table 16), indicating that students of all groups gained significant knowledge through the inquiry activity, $t(61) = 10.19$, $p < .001$.

7.3.4 Effects of Prompts on Knowledge Test Results

In accordance with time on task, an ANOVA showed no differences among the three treatment groups on the pretest, $F(2, 62) < 1$, $MSE = 5.62$, revealing that the balancing of the groups concerning their average pre-knowledge on photosynthesis before starting the inquiry cycles was effective.

A first ANOVA on knowledge test performance showed significant differences between three sciences classes from which the participants were recruited, $F(2, 66) = 7.46$, $MSE = 44.58$, $p = .001$, $eta^2 = .18$. Thus, the results of the following analyses were adjusted for class differences by including class as a control factor entered first in the linear (ANOVA) model with sequential decomposition of variance.

A second ANOVA on knowledge test performance (Table 16) with class as a control factor showed significant differences between the treatment groups, $F(2,64) = 3.79$, $MSE = 5.51$, $p = .028$, *partial* $eta^2 = .11$. Planned comparisons showed that students in the regulation group outperformed, as expected, students in the explanation group, p(one-tailed) = .006, d(unadjusted) = 0.65, as well as students in the basic inquiry group, p(one-tailed) = .027, d(unadjusted) = 0.57. There was no significant difference between the explanation group and the basic inquiry group, p(two-tailed) = .786, d(unadjusted) = 0.08.

Table 16. Descriptive Statistics for Pretest and Dependent Variables

Treatment Groups		**Knowledge Pretest**	**Knowledge Posttest**	**Explanation-Application Test**
Regulation Group	M	9.75	13.76	.67
	SD	2.19	2.05	.75
	N	24	25	21
Explanation Group	M	9.12	12.14	.17
	SD	2.49	2.83	.48
	N	25	28	21
Basic Inquiry Group	M	9.75	12.38	.17
	SD	2.44	2.94	.33
	N	16	16	12
Total	M	9.51	12.78	.36
	SD	2.35	2.67	.62
	N	65	69	54

7.3.5 Effects of Prompts on Explanation-Application Test Results

Again, a first ANOVA was calculated to test for science class differences in the explanation-application test results. With $F(2,51) < 1$, MSE = 0.10, there was no need to adjust the results of the following analyses for class differences.

A second ANOVA on explanation-application test performance (Table 13) showed significant differences between the treatment groups, $F(2,51) = 4.81$, $MSE = 0.33$, $p = .012$, $eta^2 = .159$. Planned comparisons indicated that students in the regulation group, as expected, engaged significantly more in scientific reasoning than students in the explanation group, p(one-tailed) = .004, $d = 0.80$, and in the basic inquiry group, p(one-tailed) = .010, $d = 0.83$. Again, there was no significant difference between the explanation group and the basic inquiry group, p(two-tailed) = 1.000, $d = 0.00$.

These results of the explanation-application test show that, during inquiry cycle III, the regulation group outperformed both the explanation group and the basic inquiry group in terms of scientific reasoning. Thus, the regulation prompts provided in the first two inquiry cycles were effective in order to engage students in scientific reasoning even when students were no longer prompted to do so. On the other hand, the results show that simply prompting for explanations (without prompting for regulation) was not effective in encouraging scientific reasoning.

7.4 Discussion

Following ideas of Mayer and others (Kirschner et al., 2006; Mayer, 2004), the basic assumption of the present study was that successful inquiry learning needs instructional support. In this study, the focus was on scientific reasoning during inquiry learning that can be encouraged by prompting for explanations. However, successful scientific reasoning during an inquiry cycle requires students to regulate their flow of thoughts appropriately. Thus, it was expected that prompting for explanations should be accompanied by prompting for regulation in order to improve the effectiveness of inquiry learning in terms of scientific understanding.

The results are in line with the basic assumptions. The regulation prompts had positive effects on students' performance in both the knowledge test and the explanation-application test. That is, the regulation group (being prompted for explanation and regulation; receiving advanced inquiry support) outperformed the basic inquiry group (receiving basic inquiry support only). In addition, the regulation group outperformed the explanation group (being prompted for explanation without being prompted for regulation; receiving advanced inquiry support as well). However, the explanation group did not outperform the basic inquiry group. Apparently, the explanation prompts and the advanced inquiry support provided in the explanation group did not lead to an advantage compared to the basic inquiry group receiving minimal inquiry support only. In sum, the results of the present study show that supporting regulation during inquiry learning promotes the acquisition of knowledge and scientific reasoning.

One finding of specific interest is that students in the regulation group apparently internalized the regulation of their flow of thoughts when exercising to give explanations in the first two inquiry cycles, because even in the absence of regulation prompts (during the third inquiry cycle that functioned as an explanation-application test), students in the regulation condition outperformed students in other conditions in terms of scientific reasoning. Especially when relations between variables were non-linear or not proportional, students in the explanation and basic inquiry groups tended to oversimplify relationships and, hence, did not engage in accurate scientific reasoning. For example, we found that students in the explanation and basic inquiry conditions presented non-linear relationships inadequately. Learners tended to describe linear relationships between variables even when relationships were non-linear. For instance, one student explanation was: ”CO_2 will have the same effect as light: Increasing CO_2 will lead to more Biomass”. Even though data results of experiment runs indicated non-linear relationships between variables, the student simplified relations. However, students in the regulation group were able to explain non-linear relationships between variables accurately. For instance, one student explanation was: “Increasing CO_2 will lead to an increasing biomass production, but only up to a certain point. At a certain point, the plant cannot take up more CO_2. This effect is different to the effect of light on biomass production”. Here the student points out the relationship of both independent variables with the dependent variable. Additionally, the student mentions the difference in quality (linear vs. non-linear) of the relationships. These findings support that simply promoting explanations in inquiry is not sufficient. Students need to be encouraged to plan, monitor, and evaluate, that is, to regulate their flow of thoughts. Regulation prompts seem to be a promising way to provide this encouragement.

As reported above, we found no significant differences in performance between the explanation group and the basic inquiry group in terms of knowledge acquisition and explanation-application. Several reasons might be responsible for this observation: One reason may be related to spontaneously making notes, which was an option in the *FreeStyler* workspace in all conditions. The learning environment *FreeStyler* offers a note pad on the workspace throughout the inquiry cycle. While both groups, the explanation and the regulation groups, were explicitly prompted to explain, the basic inquiry group was allowed to make notes spontaneously but was not prompted to do so. An analysis of the log-files showed that students in the basic inquiry group spontaneously used the provided note pad to write explanations. As a result, this may have reduced the difference between the explanation group and the basic inquiry group, so that the self-explanation effect (Chi & Bassok, 1989; Chi et al., 1994) could not be replicated in the present study.

Another reason for not finding any performance differences between the explanation group and the basic inquiry group might be the following: The explanation group received advanced inquiry support whereas the basic inquiry group received only basic inquiry support. That is, during the orientation phase of an inquiry cycle, the explanation group (as well as the regulation group) worked with an advanced version of a modeling workspace for developing a causal-loop diagram whereas the basic inquiry group worked with a basic version of that workspace. The advanced version gave the learners more potential to represent relationships between variables than the basic version. We expected that a causal-loop activity in the advanced version provides affordances for students to represent their understanding more precisely. It is an open question, however, whether the advanced version might have been too complex, leading to cognitive overload and, thus, to a disadvantage that could not be compensated in the explanation group. However, in the regulation group this potential disadvantage did not seem to affect students' learning performance.

Another reason why receiving explanation prompts didn't lead to more learning gain in comparison to receiving no explanation prompts is related to the nature of inquiry tasks. In contrast to other activities, inquiry activities afford opportunities to reflect. Inquiry activities consist of tasks such as developing a hypothesis and examining collected data, which inherently provoke reflection. For instance, formulating a hypothesis entails externalizing the learner's thoughts with respect to one variable affecting another. In contrast, the task of reading a paragraph doesn't provoke reflection. The explanation prompts might have not lead to a strong effect, because students following the inquiry cycle engaged in reflection automatically even if not prompted. This is in accordance to findings by Moreno and Mayer (2005), which suggested that the nature of the task might decide on whether direct explanation support is effective or not. Moreno and Mayer (2005) found that when crossing direct explanation support (support vs. no support) with interactivity (interactive environments vs. non-interactive environment), explanation support failed to be effective if the nature of the task requires interaction.

A question of theoretical as well as practical relevance is how students can be supported to internalize the regulation processes even more, encouraged by regulation prompts, and to integrate their knowledge in the context of inquiry learning even better. One approach is to scaffold learners during a learning activity (Hmelo-Silver et al., 2007; McNeill et al., 2006; Quintana et al., 2004). Scaffolding involves a fading procedure in order to reduce instructional support or guidance continuously. Fading, however, needs adaptation (Leutner, 1993, 2004). One way to adapt prompts to learners' needs is to take into account the learner's existing knowledge. Dependent on a learner's zone of proximal development, a fading mechanism can be integrated to achieve a high level of autonomy. This mechanism is currently being investigated in the area of intelligent tutoring systems (Conati & VanLehn, 2000).

Another way of adapting prompts is to allow the learners to determine the level of coercion by themselves. In exploratory pre-studies, we implemented and tested various prompt types and varied their level of coercion systematically. For example, pop-ups and alerts are salient prompts that force the learner to interrupt the experimentation flow immediately. This might be useful depending on the nature of prompts, but it turned out to be disadvantageous for regulation prompts because students quickly became frustrated and stopped writing explanations. We also implemented on-demand prompts and found that students did not make the effort of clicking a button to get information. On-demand prompts might be effective for situations in which students need specific information (Kuhn et al., 2000). In the present case, however, students were fully equipped to run experiments successfully; hence the pilot tests showed that only few students used on-demand prompts, and this happened mostly after they had written their explanations. Thus, a step for extending the present work is to implement regulation prompts within a fading procedure that reduces the level of coercion by using different types of prompts.

"I think these results are somehow correct because it makes sense now :D. Why can't the plant take up more CO_2? What does the saturation depends on? When that is known, can you increase the saturation by other factors, such as sunlight?"

(Student from Katedral School, Sweden)

8 Overall Discussion and Outlook

This chapter aims at taking a step back to describe general conclusions. The main question that derived from the problem statement and the findings of the exploratory study was:

What is the effect of regulation prompts on outcomes, specifically knowledge acquisition and explanation-application in a computer-based inquiry learning context?

Theoretical Basis. Starting from a process model that is based on prominent approaches in inquiry learning (de Jong & Njoo, 1992; Kuhn et al., 2000), problems that learners face during inquiry learning have been described. The focus in inquiry learning has been the role of explanations, the importance of articulating them and the problems when doing so. According to inquiry learning research (Brewer et al., 1998; Klahr & Dunbar, 1988; Kuhn et al., 1992), scientific reasoning was identified to be an important aspect that students should engage in. Based on a distinction of processes taking place at a meta-level and an object-level (Nelson & Narens, 1994), research on metacognition (Brown, 1987; Flavell, 1987; Schraw & Moshman, 1995) and inquiry learning have been combined. A suggestion for multi-level support, consisting of inquiry support, explanation support and regulation support, has been provided. Specifically regulation support has been shown to be important in inquiry learning for two reasons. One reason is that regulation processes that are necessary for inquiry learning were lacking in many students because of a production deficiency (Flavell, 1987) and not an availability deficiency (Veenman et al., 2005). Another reason is that research investigating the self-explanation effect suggested that learners do not produce high-quality explanations spontaneously. This shortcoming was tackled by providing explanation support. Both reasons suggested that prompting is an effective format to offer explanation support. However, derived from research in the area of self-explanation research, explanation support was only effective for some students (Aleven & Koedinger, 2000; Renkl, 1997) and based on multi-media learning research, the effectiveness of explanation support was found to be depending on the nature of the task (Moreno & Mayer, 2005). For inquiry learning, explanation support was not sufficient, and therefore explanation support needed to be augmented. Derived from research by Kuhn and colleagues (Kuhn et al., 1995), the engagement in regulation processes was assumed to be of prime importance to foster scientific reasoning. Findings with respect to regulation prompts showed promising effects in the context of inquiry learning (Coleman, 1998; Davis, 2003; King & Rosenshine, 1993; Lin & Lehman, 1999), but certain rules must be taken into account to design effective regulation prompts. Overall and in line with the research literature, advanced inquiry support is expected to be above all necessary to enable learners to learn during an inquiry cycle effectively.

Instructional Approach and Learning Environment. In order to be able to design and assess effects of regulation prompts, students' regulation behavior in an inquiry learning setting had to be observed. An exploratory study revealed problems to engage in deliberate regulation and a tendency to write descriptive explanations lacking scientific reasoning. Based on the findings of the exploratory study and the theoretical premises, regulation prompts according to identified problems in the respective inquiry phases were developed. To test the effectiveness of regulation support, an instructional approach was adopted based on White and Fredriksen's (1998) ideas on inquiry learning. This newly developed approach called Reflective Prediction Cycle guided the adaptation of the model-based environment *FreeStyler*. *FreeStyler* was adapted using an *IMS/LD* script, which consists of an activity structure that guides a learner through the respective inquiry phases and additionally offers prompts. The activity structure in *FreeStyler* guided the student through the phases of two inquiry cycles. The scripted *FreeStyler* environment was found to be effective in the pilot study, because hypothesized effects could be measured appropriately. In addition, an assessment of perceived use with respect to prompts was found generally as helpful and not mentally exhausting. Still, small improvements were planned, which were in line with findings from existing research on using prompts in inquiry environments (Linn & Slotta, 2000).

Assessment. Besides the environment, an assessment instrument was successfully developed and tested in the pilot study, a *knowledge test*. Based on the results from the pilot study, the knowledge test needed some adaptation. The declarative part of the knowledge test revealed ceiling effects, which is similar to findings from other studies that measured effects of regulation prompts (King & Rosenshine, 1993; Lin & Lehman, 1999). The procedural part of the knowledge test, however, revealed group differences as expected. For the main study, the procedural part of the knowledge test was emphasized by adding more transfer items. With respect to content analysis of explanations, it could be successfully shown that students receiving regulation support produced better explanations than students receiving explanation support alone. The procedural part of the knowledge test provided some indications that this effect persisted even if regulation prompts were not presented. To confirm these indications, a dependent variable was added to the main study that measured whether there was a sustained effect on the quality of explanations in terms of scientific reasoning. This was done by adding a third inquiry cycle and providing equal prompts to all groups. This *explanation-application test* was added under the assumption that the quality of explanations can be used as a performance indicator (e.g., Sandoval, 2003). In addition, the explanation-application test was contributing to existing research on regulation processes by providing an instrument to measure sustainability of prompting effects.

Support. The development and validation of assessment instruments permitted to investigate whether the prompting effects from the pilot study could be confirmed in the main study. Because some instruments had to be adapted because of low internal consistency, reliability of instruments was assessed again in the main study. In addition to the explanation group and the regulation group, a third group, called basic inquiry group was added that served as a baseline receiving minimal support in terms of inquiry and no support with respect to explanation and regulation. This third condition of basic inquiry support was assumed being less effective than advanced inquiry support that was offered in the explanation group and the regulation group. In line with Mayer and others (Kirschner et al., 2006; Mayer, 2004), minimal guidance was assumed to be less effective than offering advanced inquiry support. In sum, the study design for the main study consisted of the same groups as in the pilot study (explanation group and regulation group) plus a basic inquiry group. The results confirmed the indications from the pilot study. Students in the regulation group outperformed students in the explanation group with respect to explanation-application and knowledge. In addition, the regulation group outperformed the basic inquiry group. However, students in the explanation group did not outperform students in the basic inquiry group. Based on the wide agreement that providing guidance is beneficial (Hmelo-Silver et al., 2007), the minimal guidance that was offered in the basic inquiry support group should have lead to a disadvantage with respect to knowledge and explanation-application. However, in comparison to the explanation group there was no significant difference with respect to knowledge performance and explanation-application performance. Several reasons might have lead to that result. According to Chi and colleagues (Chi et al., 1989), students who construct explanations have an advantage over students who do not explain. This advantage results in the *self-explanation effect* (Chi & Bassok, 1989; Chi et al., 1994). This effect could not be replicated because students in the basic inquiry group did construct explanations despite the fact that they were not explicitly requested to do so. This is in contrast to Atkinson and others (e.g., Atkinson et al., 2003) who claim that students rarely formulate explanations spontaneously. Another factor contributing to the lacking advantage of the explanation group in comparison to the basic inquiry group might have been related to the nature of inquiry itself. As students followed the inquiry cycle, the phases of inquiry might have afforded reflective processes automatically, so that explanation prompts became redundant. This explanation of missing prompting effects is in line with findings by Moreno and Mayer (2005) who showed that explanation support is ineffective for tasks that afford reflection. Another factor that might have removed the advantage of the explanation group was the advanced inquiry support that was offered in the explanation group but that was reduced to minimal support in the basic inquiry group. The goal of advanced inquiry support was to engage students in deeper processing during the orientation phase, however instead of deeper processing it might have lead to a mental exhaustion and thus to a exhaustion of the working memory (Baddeley, 1992), which prohibited deeper processing.

Nevertheless, the main study was able to confirm an advantage for the regulation group in comparison to both the explanation group and the basic inquiry group, which was the driving question of the present dissertation. Based on the assumption that scientific reasoning plays an important role in inquiry learning (Klahr & Dunbar, 1988; Kuhn et al., 1992), it was shown that students who receive regulation prompts sustainably articulate better inferences and justifications in terms of scientific reasoning. This complies with the assumption that in the case of inquiry learning provoking thought by offering explanation support is not sufficient. In addition, learners must be supported to regulate their flow of thoughts to engage in scientific reasoning. The results showed that this could be accomplished by providing regulation support. At the same time, students in the regulation group also gained more knowledge than students gained in the other groups. This confirms results that regulation prompts are an effective means leading to a learning gain in comparison to other types of prompts (e.g., Lin & Lehman, 1999). In line with the assumption that students don't suffer from an availability deficiency but from a production deficiency (Veenman et al., 2005), prompts were effective in activating processes that lead to deeper processing (Reigeluth & Stein, 1983). It confirms the assumption that in inquiry learning, explanation prompts should be augmented with regulation prompts.

Theoretical Implications. This dissertation contributes to research in inquiry learning in various ways. Based on a distinction between meta-level and object-level, it confirms approaches to inquiry learning (de Jong & Njoo, 1992; Kuhn et al., 2000) with respect to the important role of regulation processes in inquiry learning. Furthermore, it confirms the need to support regulation during inquiry learning with emphasis on fostering scientific reasoning. In addition, it contributes to research investigating prompting by providing evidence that prompting can lead to sustained effects with respect explanation behavior. This confirmed the assumption of a production deficiency (Veenman et al., 2005).

Practical Implications. Several practical implications derive from this dissertation. An instructional approach was developed that can be applied for classroom instruction for various science subjects. A learning environment was adopted including the redesign of a plug-in for developing causal loop diagrams and the realization of an activity structure using *IMS/LD* scripts that has the potential to be re-used for supporting other subjects besides Biology. In addition, the *IMS/LD* script is potentially transferable to other learning environments than *FreeStyler*. Besides the learning environment, assessment instruments have been developed and validated in a pilot study. A knowledge test has been developed to assess students' declarative and procedural knowledge with respect to inquiry and photosynthesis. With respect to analyzing the quality of explanations, a coding method was developed to determine the presence or absence of scientific reasoning. Assessing the quality of explanations as a dependent variable in a third inquiry cycle contributed to the method of online assessment, which is assumed more valid than offline assessment (Veenman, 2005). Furthermore, regulation prompts were developed which are tailored to inquiry phases in an inquiry cycle.

Limitations. In this dissertation, regulation support in the context of explanation-based inquiry learning was investigated. Hence, results can only include statements about the effectiveness of regulation prompts in combination with explanation prompts. It cannot make statements about the effect of regulation prompts in isolation from explanation prompts. However, some findings exist outside the area of inquiry learning. Findings from research in journal writing indicate that regulation prompts alone might not be effective. Berthold and colleagues (Berthold et al., 2007) found that metacognitive prompts that are provided alone do not lead to higher learning outcomes. It must be noted that metacognitive prompts were provided during a follow-up activity of journal writing, which is in contrast to prompts used in this dissertation, where prompts were offered during the activity. Findings from research in problem solving indicate that regulation prompts indeed have an effect on learning outcome even if provided in isolation. Veenman and colleagues (Veenman et al., 2005) provided young learners with metacognitive cues, which they were asked to apply during problem solving and thinking aloud. Results showed that providing these cues lead to higher learning outcomes than not providing these cues. The results suggest that in the case of an inquiry learning activity similar results could be expected. However, it is possible that the nature of inquiry learning can be of disadvantage when testing the effect of regulation prompts in isolation of other prompts.

Future Work. Based on the findings from the studies comprised in this dissertation, follow-up research questions can be suggested. A next step is to provide a computer-based environment including prompts that are adaptive to task difficulty and learner's capabilities. The development of prompts used in this dissertation was based on student's explanation behavior that was observed in the exploratory study. Hence, prompts were provided to meet the needs during specific phases of the inquiry cycle. However, prompts were not adapted to the current learner's behavior. To take into account the current learner's behavior, pedagogical agents may be useful. Pedagogical agents can analyze the progress of a learner and the quality of explanations and provide prompts that are informed by outcomes of this analysis. One method to provide adapted prompts is to compare the learner's current explanation behavior to a reference model, which is an expert model that includes the optimal explanation behavior. If the learner deviates from the reference model, regulation prompts are offered that considers the deviation. This approach has been adopted in the area of inquiry learning, specifically *system-dynamics modeling*. Anjewierden and colleagues (Anjewierden, Chen, Wichmann, & Borkulo van, 2009) have an approach in which system -dynamics models are compared to a reference system-dynamics model to provide adaptive prompts. Considering analyzing explanations, data mining techniques can be applied to determine the deviation from the reference explanation. Prompts can be adapted in many effective ways. They can be faded, they can be provided in different formats (coercive vs. not coercive), and they can trigger different regulation processes. The adaptation of learning environments according to learners' behavior has been the focus in the area of Intelligent Tutoring Systems (e.g., Aleven & Koedinger, 2002).

Another aim of future studies should be to re-examine the role of guidance in relation to regulation prompts. Based on the accepted assumption that guidance is necessary to succeed in inquiry learning (Hmelo-Silver et al., 2007), advanced support was provided in the explanation group and in the regulation group and only minimal support was provided in the basic inquiry group. Even if the basic inquiry group had learned less than the regulation group, it would not have been clear whether advanced support contributed to that fact. A future study should examine the role of support by crossing regulation support and inquiry support.

In addition, the role of interactivity with respect to regulation prompts is be of interest. As Moreno and Mayer (2005) found, explanation prompts were not effective in the context of interactive tasks. In the present dissertation, it was shown that this finding could not be transferred to prompting regulation processes, as regulation prompts were effective even in inquiry learning, which is considered highly interactive. For future studies, it will be interesting to examine the role of interactivity and possible interaction effects with regulation prompts.

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Appendix

Appendix A: Knowledge Pre- and Posttest

Appendix B: Perceived-Use Questionnaire (Pilot Study only)

Appendix C: Frequencies in Exploratory Study

A Knowledge Pre- and Posttest

Questions about Photosynthesis

The following questions are about photosynthesis and science in general.
Please circle the correct question. There is only ONE correct answer for every question.
Some questions require an explanation.

What are the 3 components that plants use in the photosynthesis process?

a. Oxygen, light, water
b. Glucose, light, water
c. Carbon dioxide, light, water
d. Stomata, light, water

The photosynthetic process removes ____________ from the environment.

a. Soil
b. Sugar
c. Oxygen
d. Carbon dioxide

At what time can the plant take in big amounts of CO2?

a. Night
b. Day
c. Day and night

Biomass can be from:

a. Crops and trees
b. Soil
c. Water
d. Air

In a greenhouse, you are dropping the light intensity from 100% to 0%. What will happen with the plants?

a. The photosynthesis rate will increase
b. The water absorption will increase
c. The photosynthesis rate will decrease
d. The temperature will increase

In a greenhouse, you are increasing the light intensity from 0% to 100%? What will happen with the plants?

a. The photosynthesis rate will increase
b. The water absorption will decrease
c. The photosynthesis rate will decrease
d. The temperature will decrease

Whenever scientists carefully measure any quantity many times, they expect that

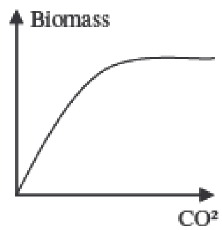
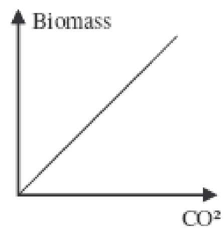
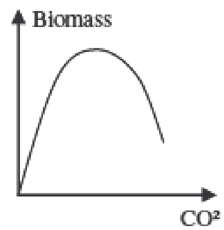
a. All of the measurements will be exactly the same
b. Only two of the measurements will be exactly the same
d. All but one of the measurements will be exactly the same
e. Most of the measurements will be close but not exactly the same

Maria collected the gas given off by a glowing piece of charcoal. The gas was then bubbled through a small amount of colourless limewater. Part of Maria's report stated, "After the gas was put into the jar, the limewater gradually changed to a milky white colour."
This statement is

a. An observation
b. A conclusion
c. A generalization
d. A hypothesis

Pick a shape that represents best the effect of **exceeding** CO^2 on biomass production. Note that the plant will be sufficiently supplied with all other components (water, nutrients etc.).

Experiment Conditions:
Duration of the experiment: 28 Days
Number of Runs: 10 (increasing CO^2 with up to **10 000 ppm**)

A	B	C
		

Explain your decision:
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Pick a shape that represents best the effect of **little** CO^2 on biomass production. Note that the plant will be sufficiently supplied with all other components (water, nutrients etc.).

<u>Experiment Conditions:</u>
Duration of the experiment: 28 Days
Number of Runs: 10 (increasing CO^2 with up to **20 ppm**)

<table>
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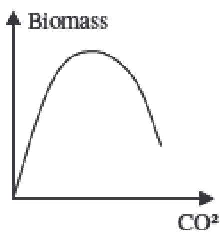
<td>
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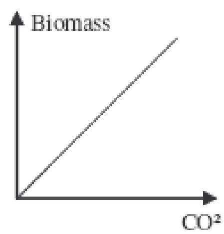
<td>
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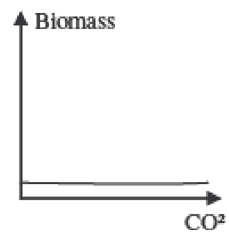
<td>
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Explain your decision:

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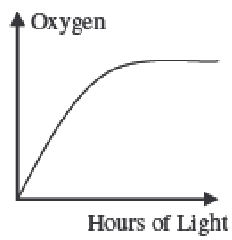
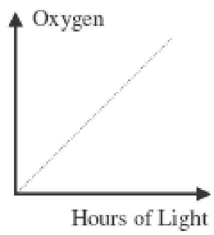
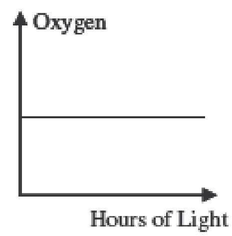
Pick a shape that represents best the effect of **24h of light** on **oxygen** production. Note that the plant will be sufficiently supplied with all other components (water, nutrients etc.).

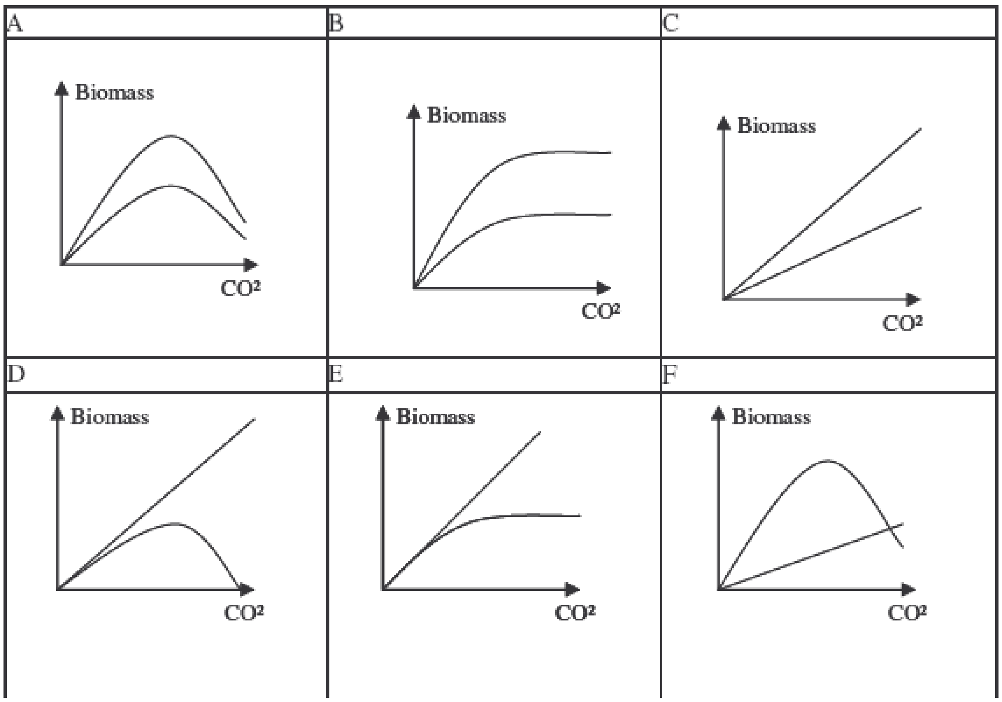
Experiment Conditions:
Duration of the experiment: 28 Days
Number of Runs: 10 (increasing hours of light with up to **24h**)

A	B	C
		

Explain your decision:

Pick a shape that represents best the effect of **exceeding** CO^2 by **5h** of light and **24h** of light on biomass production. Note that the plant will be sufficiently supplied with all other components (water, nutrients etc.).

<u>Experiment Conditions:</u>
Duration of the experiment: 28 Days
1. Experiment by 5h of light: Nr of Runs: 10 (increasing CO^2 with up to **10 000 ppm**)
2. Experiment by 24h of light: Nr of Runs: 10 (increasing CO^2 with up to **10 000 ppm**)



Explain your decision:

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B Perceived Use Questionnaire (Pilot Study)

The following questions will be related to your experience with Freestyler:
You will be asked what you think about the following statements. There are no correct or wrong answers. Your opinion is what we want.

Please circle one number for every statement. **1** means "I don't agree at all", **3** means "I somewhat agree" and **5** means "I completely agree".

	I don't agree at all		**I somewhat agree**		**I completely agree**
The prompts were helpful for successfully running the experiment.	1	2	3	4	5
The prompts helped me to write down my thoughts.	1	2	3	4	5
During difficult phases of the experiment, it was helpful to follow the prompts to write down explanations.	1	2	3	4	5
Receiving the prompts was quite exhausting.	1	2	3	4	5
The prompts helped me to go through the experiment systematically.	1	2	3	4	5
The prompts distracted me from the actual task.	1	2	3	4	5
I could have done the experiment better without prompts.	1	2	3	4	5

C Frequencies in Exploratory Study

Frequencies for regulation processes:

Category	**Subcategory**	**Frequency**	**In Percent**
Planning		6	6%
Monitoring		9	9%
Evaluation	About self	51	52%
	Anticipated thinking	33	33%
Total		**99**	**100%**

Frequencies for quality of explanation:

Category	**Frequency**	**In Percent**
Causality	51	55%
Complexity	24	26%
Consistency	18	19%
Total	**93**	**100%**
Combination of all	9	7%