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MARIO MÄEOTS

Inquiry-based learning in a web-based learning environment: a theoretical framework of inquiry-based learning processes

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Science Education Centre, Faculty of Science and Technology, University of Tartu, Estonia

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LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following original publications, which are referenced in the text by their Roman numbers:

I. **Mäeots, M.**, Pedaste, M., & Sarapuu, T. (2008). *Transforming students' inquiry skills with computer-based simulations.* Paper presented at the 8th IEEE International Conference on Advanced Learning Technologies, Santander, Spain. doi: 10.1109/ICALT.2008.239

II. **Mäeots, M.**, Pedaste, M., & Sarapuu, T. (2011). *Interactions between inquiry processes in a Web-based learning environment.* Paper presented at the 11th IEEE International Conference on Advanced Learning Technologies, Athens, USA. doi: 10.1109/ICALT.2011.103

III. Pedaste, M., **Mäeots, M.**, Leijen, Ä., & Sarapuu, T. (2012). Improving students' inquiry skills through reflection and self-regulation scaffolds. *Technology, Instruction, Cognition and Learning, 9*, 81–95.

IV. **Mäeots, M.**, & Pedaste, M. (2014). The role of general inquiry knowledge in enhancing students' transformative inquiry processes in a web-based learning environment. *Journal of Baltic Science Education, 13*, 19–31.

The author contributed to the publications as follows:

For Paper I: designing the study, formulating the research questions, planning and carrying out data collection and analysis, writing the paper as the main author.

For Paper II: designing the study, formulating the research questions, planning and carrying out data collection and analysis, writing the paper as the main author.

For Paper III: participating in the creation of the study design, working out the instruments of the study, participating in the formulation of the research questions, planning and carrying out data collection and analysis, writing the paper as the second author.

For Paper IV: participating in the creation of the study design, working out the instruments of the study, participating in the formulation of the research questions, planning and carrying out data collection and analysis, writing the paper as the main author.

1. INTRODUCTION

One of the goals of European countries in the past 20 years has been encouraging more students to study science (Eurydice network, 2011), referring to the declining interest in science related careers. During this period, numerous proposals and curriculum reforms in many countries (including Estonia) have been made to achieve this goal. Inquiry-based learning is an umbrella term in many of the documents underlying curriculum reforms, and is considered to be the main tool for engaging students to study science. Common sense is that mainly deductive science-teaching methods should be reversed to more inquiry-based learning methods, as is stated in the European-level strategic document "Science Education Now: A renewed Pedagogy for the Future of Europe" (Rocard, Csermely, Jorde, Lenzen, Walberg-Henrikson, & Hemmo, 2007) emphasizing the importance of inquiry-based learning.

In Estonia the reversing started in 2002, when science curricula were modified toward more problem-based learning, and even a more inquiry-based approach was introduced in science curricula in 2011 (Gümnaasiumi riiklik õppekava, 2011; Põhikooli riiklik õppekava, 2011). Problem-based learning is defined as an inductive pedagogical approach to solve, e.g., real-life problems (Hmelo-Silver, 2004; Prince & Felder, 2006). While inquiry-based learning in general overlaps with problem-based learning, it encompasses different teaching types that are not common for problem solving (Spronken-Smith, & Walker, 2010; Prince & Felder, 2006). Staver and Bay (1987) distinguished three types of inquiry-based teaching; this was later modified by Spronken-Smith and Walker (2010). According to that, inquiry-based teaching could be as:

- structured inquiry – teacher has the central role, providing the problem and an outline for solving it;
- guided inquiry – teacher provides the question, but students plan and carry out activities to find an answer to the question;
- open inquiry – students state their own questions and plan and carry out activities to find an answer to the question.

Therefore, two sub-terms – inquiry-based learning and inquiry-based teaching (=inquiry-based instruction) – can be distinguished under the term "inquiry" in a broad or inquiry-based approach as used in the current thesis (sometimes referred to as inquiry approach or inquiry-based methods). The first describes the learning process from students' perspective; the latter describes how the teaching process is organized and what the role of the teacher is. The focus of the current study was on students. Thus, in this study, the term inquiry-based learning (sometimes referred to as inquiry learning or (students') inquiry or inquiry process) is considered as the main concept. However, based on the learning-related data collection and findings, discussion and recommendations will again be broadened to include inquiry-based teaching.

Returning to the curricula reforms, any change in teaching will not be successful if teachers lack the willingness or knowledge to implement new approaches. This may sound overly critical, but several studies reveal that teachers are often not ready to use inquiry-based learning (e.g., weak understanding of the nature of science, lack of time) or even if teachers do report their teaching as inquiry-based teaching, they actually do not teach science according to an inquiry-based approach (e.g., Capps & Crawford, 2013; Furtak, 2006; Kidman, 2011). Therefore, there is a clear need for teacher training (e.g., Kask, 2009), but, moreover, a need for designing and developing relevant learning materials that help teachers to update their teaching methods so that their lessons are more inquiry-based (Chang, Sung, & Lee, 2003). Furtak (2006) adds that before implementing any learning material there is a need to explore how inquiry-based teaching looks like in average classrooms. This allows the refining of appropriate learning materials to the teachers of varying backgrounds and levels of experience (Furtak, 2006).

In the Estonian context, much has been done to introduce inquiry-based approach – several teacher training courses (e.g., courses carried out by the Science Education Centre of the University of Tartu) have been organised, numerous supplementary materials (e.g., Kask, 2010; Pedaste & Mäeots, 2012; Pedaste & Sarapuu, 2012; Rannikmäe, 2012) have been published, and a number of specific learning environments for conducting inquiry-based learning (e.g., Pedaste, Sarapuu, & Pata, 2004; Sarapuu, 2007) have been composed. One example of such learning environment is the web-based inquiry learning environment Young Researcher (http://bio.edu.ee/teadlane/). The learning environment was developed considering the goals of the Estonian science curriculum. More specifically, it was aimed at providing a scientifically tested learning environment that improves students' inquiry knowledge and skills, as well as their domain content knowledge. In addition, the learning environment Young Researcher was used to achieve the objectives of the current study. Thus, the findings of the current study were gained in the context of web-based learning; however, in discussion and recommendations it is possible to generalize these findings so that some conclusions are also applicable in the classroom context.

Every innovation requires scientific evidence before applying it widely, especially in education, where the effect may not be easily noticeable. Based on the literature there are several studies that indicate inquiry-based learning as a successful method for science teaching. Meta-analysis conducted by Furtak, Seidel, Iverson, and Briggs (2012) showed an overall mean effect size of 0.50 in favour of the inquiry-based approach over traditional instruction. The latter is inherently teacher-centred and textbook-oriented in this context (e.g., Sungur & Tekkaya, 2006), and is thus one of the triggering arguments for the need to change the current school situation.

The outcomes of inquiry-based learning are in many cases shared as goals with traditional instruction (Saunders-Stewart, Gyles, & Shore, 2012).

However, the difference between these approaches lies in the quantity (e.g., more domain content is learned in the case of traditional instruction) and quality (e.g., deeper understanding of how that domain content knowledge is produced is achieved in the case of inquiry-based learning) of the learning outcomes (Saunders-Stewart, Gyles, & Shore, 2012). From a similar perspective, Chang and Mao (1999) examined the efficiency of inquiry-based learning compared to traditional teaching methods on junior high school students' learning (mean age of 15 years). They came to significant results demonstrating that inquiry-based learning improves students' achievement and attitude towards subject content. Similar findings were demonstrated in the meta-analysis by Minner, Levy, and Century (2010), who synthesized the results from research conducted between 1984 and 2002 in order to clarify the impact of inquiry-based learning on students' outcomes. They revealed a not overwhelmingly optimistic but still a consistent positive trend between inquiry-based learning and the conceptual understanding of students.

Thus, there are arguments that demonstrate the significance of inquiry-based learning. But still: what ensures its benefits? In this regard conceptualizing the nature of inquiry-based learning gives clarity of its content. Research on inquiry-based learning indicates that it is a constructive and inductive form of learning in exploring a scientific phenomenon (e.g., de Jong & van Joolingen, 1998; Kali & Linn, 2007; Prince & Felder, 2006). Hence, inquiry-based learning is more student-centred and requires from students active involvement. The learning process engages students through various activities, e.g., planning investigations, researching inferences, or stating coherent arguments (Linn, Clark, & Slotta, 2003). This all leads to more meaningful learning as new knowledge is constructed by the students themselves and not acquired deductively as it is when presented by a teacher (e.g., Prince & Felder, 2006).

Moreover, the advantages of inquiry-based learning are often associated with web-based learning environments. In support of this, Kim, Hannafin, and Bryan (2007) have stated that the use of technology is one of the core approaches promoting students to learn and inquire about science.

Research claims that the use of web-based environments helps students to more effectively acquire content knowledge and inquiry knowledge and skills necessary for conducting inquiry-based learning (e.g., Eysink et al., 2009; Manlove, Lazonder, & de Jong, 2006; Plass et al., 2012; Reid, Zhang, & Chen, 2003; White & Frederiksen, 2005). Furthermore, a learning environment can increase students' awareness of the diversity of inquiry-based learning processes by engaging students in a variety of processes (Kali & Linn, 2007, p. 9). All this is contributed by a variety of opportunities that technology can provide. For example, the properties of technology offer the ability to process and store a large amount of information, the ability to present information in diverse ways, and the ability to rapidly and individually give feedback to students (Edelson, Gordin, & Pea, 1999). The role of feedback is to stimulate cognitive processes so that misconceptions will not be perpetuated (Azevedo & Bernard, 1995).

Taking advantage of these technological capabilities allows the development of several features specific to inquiry-based learning to support inquiry-based learning processes that can be applied as, e.g., in the form of scaffolds, feedback or tools. The aforementioned examples reduce the limitations that inquiry-based learning might meet, as research has declared that it is too complex for students (e.g., Krajcik, Blumenfeld, Marx, Bass, Fredricks, & Soloway, 1998; Quintana, Zhang, & Krajcik, 2005).

De Jong and van Joolingen (1998) have identified several difficulties that students might encounter while conducting inquiry-based learning (e.g., "learners may not be able to state or adapt hypotheses on the basis of data gathered", p. 5). Essentially, these problems can be related to (based on Paas, Renkl, & Sweller, 2004; Quintana et al., 2005; Sandoval & Reiser, 2003; Veermans, van Joolingen, & de Jong, 2006):

- a low level of students' cognitive and metacognitive knowledge;
- a poor level of inquiry skills;
- a lack of knowledge about particular domains;
- an increase in students' cognitive load.

Thus, an effective classroom or web-based inquiry learning environment requires an appropriate framework of inquiry-based learning processes which takes into account the role of the cognitive and metacognitive processes, and maintains a low cognitive load in one's learning. Therefore, there is a need for specific implicit or explicit scaffolds that should be integrated into the learning environment (e.g., de Jong, 2005) in order to provide possibilities to support – if needed – students in their learning.

The general aim of these features is to enable students to be more independent and help them in their inquiry-based learning. An example of this is an external memory system (e.g., notebook) that helps students to reduce their memory limitations as they navigate through a complex task (Zimmerman, 2000).

Thus, designing a web-based inquiry learning environment can be quite challenging. In this regard, the design should consider appropriate pedagogical and content perspectives (de Jong et al., 2012) and elucidate its benefits by studying and evaluating it in classroom situations. Often cited examples of such environments on the international level are Inquiry Island (White & Frederiksen, 1998), Co-Lab (van Joolingen et al., 2005), PhET Interactive Simulations (Wieman, Adams, & Perkins, 2008), and SCY-lab (de Jong et al., 2012).

The last two mentioned environments are especially valuable for Estonian teachers, because they are also available in Estonian and can thus be easily adapted to the science class without any language issues. Unfortunately, it has not been specifically investigated how and to which extent PhET simulations have been used in Estonian schools, but there is research on the SCY learning environment which confirms its implementation in several schools across Estonia (Pedaste, de Jong, Sarapuu, Piksööt, van Joolingen, & Giemza, 2013).

1.1. Goal of the study and the research problem

Recent research on inquiry-based learning has often focused on the context of supporting and developing skills and knowledge common for transformative and regulative inquiry processes (e.g., Gutwill & Allen, 2012; Manlove, Lazonder, & de Jong, 2009; Reid et al., 2003; Wu & Hsieh, 2006). Less emphasis is placed on inquiry meta-processes and on their relations to other inquiry-based learning processes. There are several studies that refer to the same issue (e.g., Quintana et al. 2005; White & Frederiksen, 2005), but it is not clear how inquiry-based learning processes relate to each other. Thus, there is a missing link in the general framework of inquiry-based learning processes; this framework needs revising by integrating all inquiry-based learning processes that are studied separately by different authors. This is the research problem to be solved in this doctoral study in the context of applying a web-based learning environment in out-of-school settings. However, after further discussions the outcomes of the current research could also be applied in classroom settings and not only in web-based learning environments.

Thus, the general goal of the current research was to construct a theoretical framework of inquiry-based learning processes that would serve as a conceptual structure for showing how the three inquiry-based learning processes – transformative, regulative, and inquiry meta-process – are related to each other. The framework of inquiry-based learning processes was developed in synthesis of literature review and empirical evidence collected by developing and implementing the web-based learning environment Young Researcher (http://bio.edu.ee/teadlane/). Thus, the construction of the framework was done in three phases: (1) construction of an initial framework based on the literature review, (2) testing the framework empirically, (3) revising the framework theoretically and testing the revised framework empirically.

In the empirical studies three sub-goals were addressed:

- to describe the process of the development of students' inquiry skills (Papers II, III, and IV);
- to specify correlations between different inquiry skills and inquiry-based learning processes (Papers II and III);
- to discover the improvement of students' general inquiry knowledge in the context of the inquiry-based learning process (Paper IV).

Taking into consideration the stated focuses three sub-studies (for more details see section 2.1.) – Sub-study I, Sub-study II, Sub-study III – were designed and conducted in which three general research questions were addressed:

- How does a web-based inquiry learning environment that is designed to support the initial framework of inquiry-based learning processes develop students' inquiry skills?
- Which correlations appear between particular regulative inquiry skills and between regulative and transformative processes of inquiry?
- How does a web-based inquiry learning environment that is designed to support the revised framework of inquiry-based learning processes improve students' general inquiry knowledge?

The learning environment Young Researcher was applied in the current study as it was developed by the research team where the author of the study belonged; therefore, it was possible to design it according to the specific needs of the current study – revising the general framework of inquiry-based learning processes – as well as considering the literature and experience with a similar learning environment Young Scientist, where the importance of web-based learning environments in inquiry-based learning was revealed (see Paper I). Thus, the learning environment Young Researcher was improved based on the results of the sub-studies of this doctoral research and the latest improvements according to the recent literature. The comprehensive development process of the learning environment Young Researcher also followed the objectives of the Estonian science curriculum, aiming to provide an environment applicable in the classroom situation. In general, the learning environment facilitates teaching by inquiry-based approach to achieve both content-related and inquiry-based learning oriented curriculum objectives.

2. THEORETICAL BACKGROUND

The following chapter provides the theoretical outline of the doctoral study. First the concept of inquiry-based learning is elucidated and then the processes and activities involved in inquiry-based learning are introduced and described. The last section of the theoretical part gives an overview of web-based learning environments and how these could be applied in the context of inquiry-based learning.

2.1. Inquiry-based learning

A review of literature characterizes the concept of inquiry-based learning by several features targeting its nature. The literature in the field outlines most often the four following characteristics (e.g., Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; Chang, Sung, & Lee, 2003; de Jong & van Joolingen, 1998; Kali & Linn, 2007; Keselman, 2003; Kolloffel, Eysink, & de Jong, 2011; Mäkitalo-Siegl, Kohnle, & Fischer, 2011; Prince & Felder, 2006):

- Discovery-oriented;
- Constructivist-based;
- Student-centred;
- Scientifically-oriented.

Inquiry-based learning is related to but furthermore derives from discovery learning (discovery-oriented). Hence theories of inquiry-based learning are usually established on theories of discovery learning. Moreover, latest research has indicated that these two terms are merging (e.g., van Joolingen, de Jong, & Dimitrakopoulou, 2007). In the current study, discovery learning and inquiry-based learning are used as synonyms.

Discovery learning is generally associated with American psychologist Jerome Bruner, who is considered one of the originators of discovery learning (see, e.g., Alfieri et al., 2011; de Jong & van Joolingen, 1998). In his works Bruner emphasizes that students' knowledge should be gained by themselves through knowledge construction – being his/her own discoverer makes content more efficiently accessible in the memory (Bruner, 1961). In the context of discovery existing knowledge is used to learn new concepts (Saunders-Stewart, Gyles, & Shore, 2012).

Using one's own existing knowledge refers to the second feature (constructivist-based) of inquiry-based learning by showing a convincing relation to the constructivist approach. Constructivist learning theory – introduced by two well-known developmental psychologists, Jean Piaget and Lev Vygotsky – stresses that students use their prior knowledge or experience to build their own knowledge (Mayer, 2004). Jonassen (1994) adds that learners construct their individual knowledge using their mental models, beliefs and prior knowledge to interpret phenomena. The role of one's experiences in learning was introduced by John Dewey, American psychologist and educational reformer. According to Dewey the main goal of learning is to develop everyday experiences, but he also emphasizes that not all experiences are educative but rather miseducative since they may falsify the growth of further experience (Dewey, 1938/1998). "An experience is not an experience unless it involves interaction between the self and another person, the material world, the natural world, an idea, or whatever constitutes the environment at hand" (Rodgers, 2002, p. 846). However, for example, Pugh (2011) states that "experiences" are too vague, and thus this goal has not been the main focus of the research of educational psychologists; "educational psychologists like to work with concepts that have greater conceptual clarity and are more easily operationalized in empirical research (p. 107). Kolb (1984) suggested integrating experience, perception, cognition and behaviour, as he described constructive *experiential learning* through the works of Lewin, Dewey and Piaget. According to the concept of experiential learning, learners need four types of abilities:

- concrete experience (learners involve themselves bias in new experiences);
- reflective observation (learners reflect on and observe their experiences);
- abstract conceptualization (learners create concepts);
- active experimentation (based on theories, learners solve problems).

However, inquiry-based learning is more focused on new knowledge construction, as experiential learning is aimed at acquiring new experiences; these experiential learning abilities are also common for inquiry-based learning. The similarity is related to their connection to discovery learning (Kirschner, Sweller, & Clark, 2006) and constructivist-based background. Bruner (1961) exemplifies constructivist-based learning by comparing two different teaching modes – expository and hypothesis-driven (discovery) – in the school situation. In the expository mode the main focus of learning is on the teacher and the student is the listener. Therefore, from a student's perspective it is a rather passive form of learning. The teacher acts as a primary source of knowledge (Worthen, 1968), and knowledge construction largely depends on what and how much a student can effectively acquire to form his/her new knowledge. However, in the hypothesis-driven approach, the learning process is more collaborative and oriented towards discovery. In this case the student has the key role in his/her learning. Therefore, targeted information is discovered by the learner (Alfieri et al., 2011), and the teacher's role is to enable the construction process as a facilitator and to provide resources (Wang, 2003).

Here emerges the third feature (student-centred) that illustrates the nature of inquiry-based learning. In this case, the student actively processes the content and the knowledge transformation is more effective and more readily available in the memory (Bruner, 1961). Accordingly, considering the historical background (e.g., Bruner, 1961; Worthen, 1968; Scott, 1972), it can be concluded that if learning is more discovery-oriented and the learning process is student-centred, the learned concepts are remembered better and entail long-term retention. However, student-centred learning is beneficial only if it is sufficiently challenging to maintain students' engagement (Bransford, Brown, & Cocking, 1999).

The last feature (scientifically-oriented) that characterizes inquiry-based learning is its scientific component. Within this context, to understand science, students need to do science (Bybee & van Scotter, 2007). In this regard, research has indicated that inquiry-based learning comprises processes which are common to scientific work where students take the role of a scientist (Chang, Sung, & Lee, 2003; Chang & Wang, 2009; Keselman, 2003; Kolloffel, Eysink, & de Jong, 2011; Madhuri, Kantamreddi, & Goteti, 2012) and therefore construct a knowledge base that comprises scientific content (McGinn & Roth, 1999).

In an inquiry-based learning situation, students mirror activities employed by scientists. For example, they ask questions; formulate hypotheses; carry out investigations or make observations; and collect evidence to propose explanations about the investigated phenomenon (de Jong & van Joolingen, 1998; Minner et al., 2010; Panasan & Nuangchalerm, 2010). Edelson, Gordis, and Pea (1999) add that inquiry-based learning has the central role in the practice of scientific work. Inquiry-based learning does not mean that there is always an experiment. It depends on the subject. For example, Gutwill and Allen (2012) investigated how to apply inquiry-based learning while students are visiting a museum. Thus, experiment is one possibility but it is not a rule that scientists always follow.

Considering all the previous theoretical aspects, inquiry-based learning can be defined as a discovery-oriented constructive student-centred learning approach where students obtain by themselves knowledge about the domain content and acquire skills and knowledge that are characteristic of scientific work. Therefore, the educational goal of inquiry-based learning is to obtain knowledge and skills that are transferable (long-term memory retention) for conducting future inquiries.

2.2. Inquiry-based learning processes

Most often, literature distinguishes two types of processes that are common to inquiry-based learning: transformative and regulative ones (de Jong and Njoo, 1992). Transformative processes rely on students' cognitive abilities and regulative processes and are more dependent on metacognitive activities (Hulshof & de Jong, 2006; Njoo & de Jong, 1993) that regulate and control other learning processes (Veenman, Hesselink, Sleeuwaegen, Liem, & van Haaren, 2014).

Significant emphasis in the context of both transformative and regulative processes is placed on scientific thinking. Scientific thinking can be recognized as cognitive control over theory and evidence entailing mental operations occurring through metacognition (Kuhn & Pearsall, 2000). With reference to this it is argued that there is a third type of inquiry-based learning process that regulates and engages competencies of transformative and regulative processes. In general it could be considered as metacognitive knowledge for action – "knowledge of how one organizes and manages one's cognitive and metacognitive processes in the course of their application" (White & Frederiksen, 2005, p. 214). In the current study it is specified as an inquiry meta-process that is related to general inquiry knowledge. In the context of the current study, general inquiry knowledge is treated as knowledge particularly pertaining to the nature of a coherent inquiry-based learning process as a whole (Paper IV).

2.2.1. Sequence of inquiry-based learning processes

Research discusses that scientific concepts are developed through a number of sequenced inquiry-based learning processes (e.g., de Jong & van Joolingen, 1998; White & Frederiksen, 1998). In literature, these processes are represented as a sequence of inquiry-based learning processes (e.g., van Joolingen et al., 2005) or many authors prefer representing it as a cycle (e.g., White & Frederiksen, 2005; Goldston, Dantzler, Day, & Webb, 2013; Hongsiri, Patcharin, Watcharee, & Pintip, 2013; Llewellyn, 2002). The latter is called inquiry cycle and is used to express the idea that students can repeat their inquiry-based learning process if, for instance, there should be a need for additional experiments. In general, there is no consensus in literature; thus, inquiry cycle and sequence of inquiry-based learning processes mostly have the same meaning. In the current study the term sequence of inquiry-based learning processes was used in this context (see sections 2.2.2).

An inquiry cycle (see Figure 1) introduced by White and Frederiksen (2005) included inquiry stages (sometimes referred to as inquiry steps, inquiry learning stages, stages of inquiry, inquiry-learning stages, inquiry phases) where students first develop a research question (Question), then generate a hypothesis (Hypothesize) and design an investigation (Investigate), record and analyse their data (Analyse), construct a model about what they found (Model), and evaluate their research process, as well as identify new questions to discover (Evaluate) that could be the starting point of a new inquiry-based learning process. By going through these steps, students obtain skills that can be used to do independent research (White & Frederiksen, 2005).

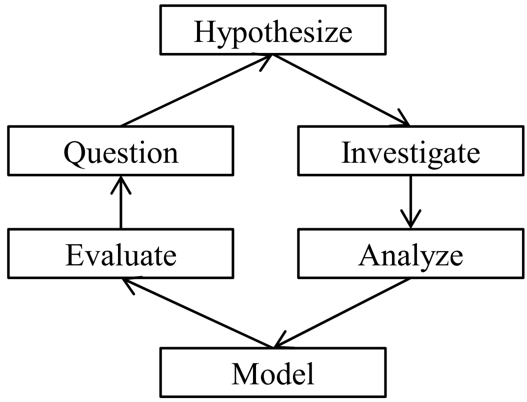

Figure 1. Inquiry cycle (White & Frederiksen, 2005).

There are several other examples of inquiry cycles that can be found in the literature. One is the "5 E Inquiry Cycle", where the teacher helps and encourages students to use five steps: Engage, Explore, Explain, Elaborate, and Evaluate (e.g., Goldston, Dantzler, Day, & Webb, 2013; Hongsiri, Patcharin, Watcharee, & Pintip, 2013; Llewellyn, 2002). However, most recent meta-analysis by Pedaste, Mäeots, Siiman, de Jong, van Riesen, Kamp, Manoli, Zacharia, and Tsourlidaki (submitted) proposes, based on a systematic review of 32 articles, an inquiry cycle where learning flows through Orientation, Conceptualization, Investigation, and Conclusion phases (see Figure 2). In the Orientation phase the domain topic is introduced, the main variables in the domain are identified and, as a result, a problem is stated. Conceptualization with two sub-phases – Questioning and Hypothesis Generation – is a phase for stating theory-based questions and hypotheses. It is succeeded by the Investigation phase, consisting of three sub-phases: Exploration, Experimentation, and Data interpretation. In general, the Investigation phase involves planning activities, data collection and ends with data analysis. Next, based on the data, main conclusions are stated in the Conclusion phase. Additionally, there is a Discussion phase, which is related to all other inquiry stages. The Discussion phase has two sub-phases – Communication and Reflection – which help students to communicate their findings to other learners and engage students to reflect on their activities in order to learn from their experiences.

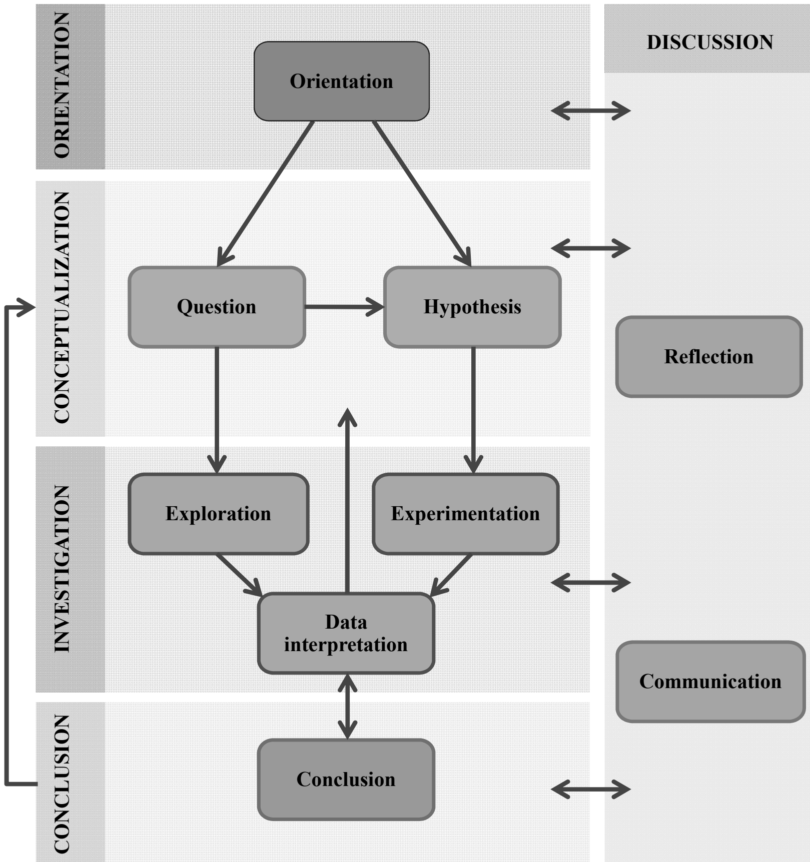

Figure 2. Inquiry cycle (Pedaste et al., submitted).

2.2.2. Transformative processes

According to the definition provided by de Jong and Njoo (1992), the main goal of transformative inquiry processes is to orchestrate students in transforming domain information into new knowledge. Students generate new knowledge for themselves through scientific reasoning comprising investigation and exploration of questions and problems (Kolloffel, Eysink, & de Jong, 2011; Lee, 2011; Friedler, Nachmias, & Linn, 1990). This process engages students to learn about scientific activities and understand how these activities work together (Singer, Marx, Krajcik, & Chambers, 2000). In this context, different inquiry skills are advocated that relate to the transformative processes. Kuhn and Pearsall (2000) classify these as scientific thinking skills that correspond as investigative and inferential activities. Investigative activities involve experiment design and evidence collection. Inferential activities are aimed at interpreting collected evidence in order to provide evidence to theory (Kuhn & Pearsell, 2000).

Research has declared that inquiry skills obtained in one situation are transferable to another, significantly different situation (e.g., Chang & Wang, 2009; Kuhn & Dean, 2008). New content knowledge is not the only outcome of inquiry-based learning, as students also complement their inquiry skills (van Joolingen, 1998). Kuhn and Pease (2008, p. 534) contrast transferable skills like rudimentary inquiry skills: "the skills of identifying an addressable question (the causal role of a specific feature), seeking informative data via controlled comparison, and drawing appropriate conclusions of causality and noncausality".

The current study relied on a list of seven transformative processes that discourse with particular inquiry skills (Pedaste & Sarapuu, 2014):

- Problem identification;
- Research question formulation;
- Hypothesis formulation;
- Experiment planning;
- Carrying out an experiment;
- Analysis and interpretation of results;
- Drawing conclusions.

In different studies, *problem identification* is almost always stated as the first stage of inquiry. Students' activities involve observing, identifying similarities and differences, and looking for patterns. The outcome of this stage is a problem statement.

Research question formulation is the second stage, where the stated problem is turned into investigable questions.

Hypothesis formulation involves providing explanations consistent with available observations, questions, and evidence. Correct hypotheses are those that have been tested through an experiment or observation.

Experiment planning involves using evidence in recognizing data patterns from which to extrapolate or interpolate more useful, testable hypotheses and algorithms.

Carrying out an experiment is divided into the steps of planning, conducting experiments, measuring, data gathering, and controlling variables.

Analysis and interpretation of results requires analytical thinking about how the data supports the controlling of the hypothesized relations, synthesizing, finding patterns, relating findings to initial questions and observations.

Drawing conclusions is a process where students have to demonstrate the results in a clear manner, choose an appropriate way to translate the outcomes to others, make representations – such as tables or diagrams that illustrate data and results – , talk to others about the study, and listen to others' evidence and explanations.

2.2.3. Regulative processes

In addition to transformative processes, several studies have shown that it is crucial to manage one's own cognition and therefore to understand that self-regulation is necessary for a successful learning process (Sitzmann & Ely, 2011; Kuhn & Dean, 2004; White & Frederiksen, 2005). Self-regulation is students' ability to direct their own learning (Boekarts, 1999); furthermore, it means taking responsibility of one's own learning (van Wyk & van der Westhuizen, 2005). Self-regulation focuses on the strategies students use to control and regulate their thinking during the learning process (Manlove, Lanzonder, & de Jong, 2007). Schraw, Crippen, & Hartley (2006) have explained that regulated learning encompasses a combination of cognition (students' abilities to encode, memorize, and recall information), metacognition (students' abilities to understand and monitor cognitive activities), and motivation (students' beliefs in their capacity to learn). In the context of inquiry-based learning, cognition involves transformative activities and metacognition involves regulative activities. Motivation describes students' beliefs that affect both the cognitive and metacognitive processes (Schraw et al., 2006). Motivation helps to promote and sustain academic achievement (Mega, Ronconi, & de Beni, 2013) and influences students' persistence in task performance (Greene & Azevedo, 2007). Moreover, motivation can be seen as "both a product, in terms of the current state of motivation, and a process, in terms of the actions taken to motivate oneself" (Greene & Azevedo, 2007, p. 363).

The success of the transformative processes largely depends on the regulative processes which keep track of the progress that has been made during transformative processes (de Jong & Njoo, 1992; Njoo & de Jong, 1993). Regulative processes are meant for controlling learning through activities like planning, monitoring, and evaluating (e.g., de Jong & van Joolingen, 1998; de Jong et al., 2005; Manlove, Lanzonder, & de Jong, 2007; Zhang, Chen, Sun, & Reid, 2004). These activities consider declarative knowledge, but also concern procedural knowledge that is required for the actual regulation of and control over one's learning activities (Veenman & Verheij, 2001). Thus, if students know that planning is necessary (declarative knowledge), they nevertheless should also have appropriate skills that are involved with each regulative process (procedural knowledge) to apply it successfully. In general, these metacognitive processes are key elements in allowing students to learn with greater understanding in producing new knowledge (Aleven & Koedinger, 2002).

According to the literature review several sub-skills can be identified which are involved in each regulative process. Considering the synthesis of selected papers, ten sub-skills were identified (see Table 1):

- *Planning* as designing the learning process is effective if students set the performance goals; predict the course of the learning process; plan their time; and make a strategic plan for sequenced learning activities;
- *Monitoring* is a process whereby a learner observes and keeps track of his/her own study process, involving activities such as taking and

reviewing notes; deciding to change the plan, if needed; and checking study time;

- *Evaluating* is a process whereby the learner evaluates the learning process and task performance (de Jong et al., 2005). Students need to check whether the learning goals have been reached; comment on the execution of the task and the entire learning progress; check the correctness of the actions and results at a conceptual level; and think about the course of learning and information processing for the future.

Table 1. Definitions of the three main regulative processes and ten sub-skills involved (based on the works of Boekaerts & Simons, 1993; Brown, 1987; de Jong, 1992; de Jong & Njoo, 1992; de Jong et al., 2005; Jacobs & Paris, 1987; Njoo & de Jong, 1993; Vermunt, 1992; Weinstein & Mayer, 1986).

Processes	General description	Sub-skills	Description of skills
Planning	Learner designs the learning process and task performance.	Setting performance goals.	Objectives for the learning process are formulated.
		Predicting the course of the learning process and planning time.	Time needed for the learning process is fixed.
		Making a strategic plan for learning activities and for their sequence.	Strategic plan for the learning process is made.
Monitoring	Learner observes and keeps track of his/her own study process.	Observing learning activities, taking and viewing notes.	Learning activities are observed.
		Deciding to change the planning.	Need for changing the initial plan is decided.
		Checking study time.	Time needed for learning activities is checked.
Evaluating	Learner evaluates the learning process and task performance.	Checking whether learning goals have been reached.	Achievement of the learning goals is checked.
		Commenting on the execution of the task and the learning process.	Comments on the execution of the learning task are made.
		Checking the correctness of actions and results at a conceptual level.	Correctness of the actions and results of the learning process is checked.
		Thinking about the course of learning and information processing for the future.	Reflection on the learning process is carried out.

In the learning environment Inquiry Island, White and Frederiksen (2005) applied metacognitive advisors that guided 5th grade students in their metacognitive activities. They described these activities through the meta-cognitive cycle in the following sequence – Plan, Monitor and Reflect. Their study results showed significant improvement in the metacognitive expertise of the 5th grade students, but also in their inquiry-based learning expertise (e.g., inquiry skills). This led to the assumption that regulative activities should be integrated into the inquiry cycle that considers both transformative and regulative activities. Based on this idea the initial framework of inquiry-based learning processes was constructed (see section 4.1.)

2.2.4. Inquiry meta-processes

In conjunction with transformative and regulative inquiry processes, it was later argued in the context of the current study that there was a third type of processes that managed cognitive and metacognitive processes. It is a broader meta-level structure or *a metacognitive knowledge for action* that helps students to understand how, when and why to activate particular transformative and regulative processes (Kuhn & Dean, 2004; White & Frederiksen, 2005). In the current study it is understood as an *inquiry meta-process* that guides transformative and regulative processes. From student perspective it considers knowledge about transformative and regulative processes on the general level. This dimension was taken into account in constructing the revised framework of inquiry-based learning processes (see section 4.5.).

What is the knowledge that is behind inquiry meta-process? For example, Schraw and Moshman (1995) represented three types of metacognitive awareness about cognition in general. They described this awareness through *Knowledge of cognition*, which includes (Schraw & Moshman, 1995, p. 352–353): (a) *Declarative knowledge* – "knowledge about oneself as a learner and about what factors influence one's performance", (b) *Procedural knowledge* – "knowledge about the execution of procedural skills", and (c) *Conditional knowledge* – "knowledge about knowing the why and when aspects of cognition". They claim that knowledge of cognition improves students' learning performance and facilitates thinking and regulating of one's learning (Schraw & Moshman, 1995).

Similarly, de Jong and Ferguson-Hessler (1996) introduced a general classification for types of knowledge in the context of problem solving, which can be seen as a component of inquiry-based learning, since, for example, inquiry-based learning is sometimes defined as a problem solving process (e.g., Chang & Wang, 2009; Lee, 2011). According to the classification, four types of knowledge can be distinguished (de Jong & Ferguson-Hessler, 1996, p. 106–107): (a) *Situational* – "knowledge about situations as they typically appear in a particular domain", (b) *Conceptual* – "knowledge about facts, concepts and principles that apply with certain domain", (c) *Procedural* – "contains actions or manipulations that are valid within a domain", (d) *Strategic knowledge* – "helps students to organize their problem-solving process by directing which stages they should go through to reach a solution". Related research has indicated that students need to know the interrelated activities that inquiry-based learning involves (Quintana et al., 2005); this has been described in the current study as inquiry meta-processes. Meta-processes need *general inquiry knowledge* that considers both conditional knowledge (Schraw & Moshman, 1995) and strategic knowledge (de Jong & Ferguson-Hessler, 1996). Students know why and when (conditional knowledge) and how to activate (strategic knowledge) specific transformative and regulative processes.

Thus, general inquiry knowledge is defined in the context of the current study as a set of knowledge about the nature of a coherent inquiry-based learning process as a whole (Paper IV). It is not knowledge about how to perform an inquiry-based task (sometimes referred to as inquiry task, inquiry-based activity, inquiry activity, inquiry problem, inquiry learning task), e.g., to formulate a hypothesis, but rather knowledge about the components of the inquiry-based learning process as a whole, including knowing the sequence of transformative inquiry stages, the necessity of each stage, and the role of metacognitive processes needed for the regulation of inquiry-based learning.

2.3. Web-based inquiry learning environments

The main educational goals of web-based inquiry learning environments are to support the acquisition of inquiry skills and to support the acquisition of content knowledge (Wecker, Kohnle, & Fischer, 2007). Technology-enhanced learning environments provide students with ample opportunities for conducting inquiry-based learning to explore a virtual world by manipulating and finding relations between variables (de Jong et al, 2012; Beishuizen, Wilhelm, & Schimmel, 2004). With advantages provided by technology, the learning process in these environments becomes more efficient, as they are seen as cognitive and metacognitive tools that support students in achieving their learning goals (e.g., Reid, et al., 2003; van Joolingen, de Jong, Lazonder, Savelsbergh, & Manlove, 2005; Azevedo, 2007). This includes acquiring higher order thinking and problem solving skills (Sethy, 2012). Edelson (2001) has stated that the role of technology is to motivate students and help them to construct and refine new knowledge. Moreover, research has stated that web-based environments:

- Can import into the classroom content of the natural world that otherwise would not be available for students, e.g., real time data of complex or dangerous experiments or the possibility to observe distant objects (Tabak & Reiser, 2008, van Joolingen, de Jong & Dimitrakopoulou, 2007);

- Allow integrating text, graphics, audio, and interactive computational objects as they can be used as multiple representations that support students' knowledge construction (Edelson, 2001);
- Provide tools that support the inquiry-based learning processes (van Joolingen, de Jong & Dimitrakopoulou, 2007);
- Can support collaboration between learners (van Joolingen, de Jong & Dimitrakopoulou, 2007);
- Allow learners to construct their theories in models that can be simulated (van Joolingen, de Jong, & Dimitrakopoulou, 2007).

As an example of a web-based inquiry learning environment, White and Frederiksen (2005) introduced Inquiry Island. It is an open-source facility designed to scaffold the use of a general-purpose inquiry model; this model is called Inquiry Cycle (Eslinger, White, Frederiksen, & Brobst, 2008). The purpose of this kind of activities was to enable students to develop their metacognitive expertise by taking on different roles while called as advisors. This perspective was also very important in designing the learning environment Young Researcher, which was applied in the current study. However, in the Young Researcher the focus was set on support mechanisms due to the complexity of regulating inquiry-based learning. According to Quintana et al. (2004), this support can help students to manage their processes of inquiry and encourage them to articulate their thinking and reflect on their learning (Hmelo-Silver, Duncan, & Chinn, 2007). Student-centred education encourages reflection by students on aspects of their own learning (Kyprianidou, Demetriadis, & Pombortsis, 2008). Reid et al. (2003) have clarified that only meaningful learning in a simulated environment can direct a learner towards the preferred learning outcomes.

3. METHODOLOGY

The current chapter is structured as follows: first, research design is introduced and data collection and sample are described in section 3.1.; next, applied instruments for data collection are introduced in section 3.2.; finally, in section 3.3., data assessment criteria and analysis methods are specified and described.

3.1. Research design

Considering the devised goals and formulated research questions (see section 1.2.), three sub-studies were designed and conducted (see Figure 3). Thereby it was possible to assemble all necessary data collected during all-Estonian competitions held from 2008 to 2011. The competitions were voluntary and students solved tasks after their school lessons. The tasks were biology-based, aiming to support achieving the objectives of the Estonian science curriculum. Participants were students from the 6^{th} to the 12^{th} grade. Due to task-specificness (experiments needed at least two persons), students participated in pairs. It also supports transferring the findings of the study into classroom context, where there is often a need to use computers in pairs, as the computer labs in many schools do not have enough computers for working individually.

Additionally, experience gathered in a previous study (see Paper I) was important for designing methods for improving and evaluating inquiry skills in the current study in the context of constructing the theoretical framework of inquiry-based learning processes.

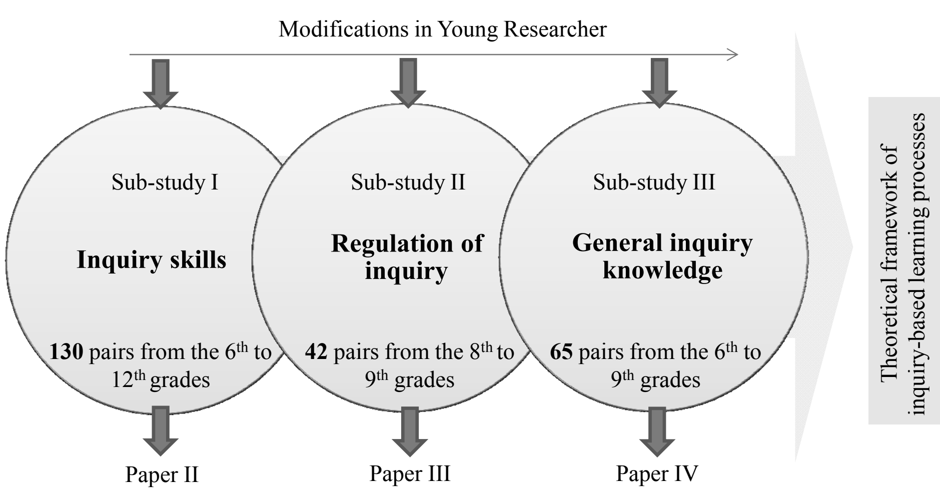

Figure 3. Design of the study.

Sub-study I was addressed to find out how the inquiry learning environment Young Researcher develops students' transformative and regulative inquiry skills. It was carried out during an all-Estonian competition where 130 pairs with 260 volunteer students from the 6^{th} to the 12^{th} grade (aged 10–18) participated. Teams of two people registered for a three-week competition. During the competition students could complete each inquiry-based task at their convenience. However, it was considered important to note that the number of pairs that started the competitions was higher than the sample of each of the sub-studies (e.g., 268 in sub-study I or 170 in sub-study III). In the analysis, only data of the pairs who finished the competition in time was used.

Sub-study II was addressed to identify which interactions appear between particular regulative inquiry skills and between regulative and transformative processes of inquiry-based learning. Similarly to sub-study I, an all-Estonian competition was organized. This time 42 pairs with 84 volunteer students from the 8^{th} to the 9^{th} grade (aged 14–16) participated. These teams of two students each were involved in a three-week competition.

In sub-study III, sixty five pairs from the 6^{th} to the 9^{th} grade (aged 10–16) participated voluntarily in an all-Estonian inquiry learning competition. The main goal of this sub-study was to clarify how the learning environment Young Researcher improves students' general inquiry knowledge. Sixty five pairs finished the competition on time, and their results were used in this study.

In all three sub-studies students solved five inquiry-based tasks in the Young Researcher learning environment. The first and the last tasks of the learning environment were used (depending on the goal of the sub-study) to assess students' transformative and regulative inquiry skills and general inquiry knowledge (depending on the sub-study). Before each sub-study the learning environment Young Researcher was modified by adding appropriate assignments and scaffolds. All these modifications considered the results of previous sub-studies and input from related research.

3.2. Instruments

1) Questions for evaluating transformative inquiry skills

Questions for assessing the development of students' transformative inquiry skills was structured on the basis of inquiry stages – formulating a research question (in many cases it can be viewed as defining a scientific problem), formulating a hypothesis, planning an experiment, analysing data, and making conclusions. The task started with an every-day story with an embedded problem which had to be solved by the students. It was an open task, where students had to write a correct research question (derived from the problem) containing the independent and dependent variables (see task 3 in Appendix 1), and the correct statement indicating a hypothetical answer to the stated question (task 5 in Appendix 1). The presence of described components was also an evaluation criterion for research and hypothesis formulation.

After that, students planned and carried out an experiment. In the planning stage, a predetermined experimental plan was already available. However, the student pairs' comprehension of the plan was evaluated by questions with multiple-choice answers (see task 7 in Appendix 1). These questions were about variables that needed to be fixed for the entire experiment, the design of the experiment, and the safety aspects that needed to be taken into account. In the case of carrying out an experiment, students conducted real experiments (see task 8 in Appendix 1). Their success was evaluated by the accuracy of the table filled in by the students during the experiment. The students also made a pre-analysis based on their results by describing the main similarities and differences in the results (task 9 in Appendix 1).

In the next stage, students could not use their own data; they were given the results of a controlled experiment made by the authors of the environment (task 10 in Appendix 1). Hence, in the analysis stage, everyone had the same results to analyse, aiming to discover the relations among the variables. This allowed everyone to be on an equal footing, even if the students' own experiment was unsuccessful. Finally, the student pairs had to formulate a conclusion that accounted for the results of the study (task 11 in Appendix 1). They had to answer the formulated research question. Students' conclusions were evaluated similarly to the hypothesis: a statement containing independent and dependent variables, and the relation between them was expected.

In the learning phase, all supportive elements described in Appendix 3 were present. All assignments for assessing students' inquiry skills and knowledge were in the form of open questions.

2) Questions for evaluating regulative inquiry skills

In order to identify the improvement of regulative processes, students were asked to set, considering the problem, their performance goals for the transformative processes (see task 2 in Appendix 1). In order to evaluate the students' strategic plan and sequence for their learning activities they were asked to write down all activities they performed during, e.g., formulating a research question (see task 3 in Appendix 1). After that, the students completed transformative activities and then reflected on regulative processes, such as monitoring and evaluation (see tasks 4, 6 and 12 in Appendix 1). The students were asked to evaluate the level of various regulative activities they had applied on Likert scale. In reflecting on their evaluation process, there was an additional open-ended question designed to encourage them to think about the course of learning and information processing, with a view to applying this method when solving inquiry-based tasks in the future (see tasks 13 and 14 in Appendix 1).

3) Questions for evaluating general inquiry knowledge

For evaluating the improvement of students' general inquiry knowledge, students identified a problem based on a real-life situation (see task 1 in Appendix 1). After that, they moved to the next step, where they planned the whole inquiry-based learning process to solve the problem. The purpose of this assignment was to explicitly perceive information about students' general inquiry knowledge in the pre- and post-tasks.

For students, a random list of six pre-defined transformative processes was provided: research question formulation, hypothesis formulation, experiment planning, carrying out an experiment, analysis of data, and drawing conclusions (presented here in the expected correct sequence). There were two assignments that measured students' general inquiry knowledge. The assignments followed the definition of the general inquiry knowledge applied in this study, containing knowledge about the sequence of transformative inquiry stages and the necessity of each stage. Thus, they first had to put transformative stages into an appropriate sequence by writing the 'queue' number after each stage as it should be done while carrying out an inquiry-based learning process. For example, students had to show that they understood that research questions should be formulated before hypotheses, and hypotheses are formed according to the research question before starting to plan experiments. This type of general inquiry knowledge is needed to plan the whole inquiry-based learning process, especially the transformative processes. Second, they were asked to explain why each transformative process is necessary in the context of inquiry-based learning and how it is related to the other inquiry stages. For example, students had to explain why careful planning is needed before starting experimentation and data collection. This type of general inquiry knowledge is especially needed to effectively plan, monitor, and evaluate – the processes that are defined as regulative inquiry processes.

3.3. Data analysis

The instruments of the study were validated through discussion with experts and through piloting. Experts were used to evaluate the constructs (e.g., questions assessing inquiry skills) and the content of the instruments. These procedures followed the rules of construct and content validity (Cohen, Manion, & Morrison, 2007). Construct validity considered theory-based assessment (e.g., how inquiry skills had been evaluated in the literature) and feedback from experts (scientists and teachers), who were asked to evaluate instrument relevance to research questions. Additionally, each instrument was piloted in the real classroom situation. The results of the piloting were discussed with experts and, based on the discussion, the instruments were improved (e.g., texts of the tasks were modified). The duration of each lesson was 45 minutes, and each time one task of Young Researcher was solved. Cronbach alpha for assessing transformative skills was 0.735 and 0.822 for regulative skills. The development of students' transformative inquiry skills and the changes in the quality of regulative activities (see assessment in Appendix 1) were analysed using non-parametric Wilcoxon tests where data was not normally distributed. Spearman correlation was used to find the relations between the quality level of regulative skills and the level of the development of transformative inquiry skills.

Students' open-ended answers for assessing general inquiry knowledge in the pre- and post-tasks were analysed according to a coding scheme based on the theoretical framework of the study (see Table 2).

Table 2. Assessment levels for analysing students' answers about general inquiry knowledge (Paper IV).

Level	Description of the level	Examples of students answers
0	Answer is not given, or it is out of the context of the assignment.	Research question formulation is something special.
1	Answer is in the context of the assignment, but the explanation is not about a particular transformative stage.	Planning means collecting data.
2	Overly general explanation about the necessity of a particular transformative process.	Drawing a conclusion is the answer to the research question.
3	Accurate explanation about the necessity of a particular transformative stage.	Experiment planning is a base for collecting data and helps us to find answers to the research questions. For that, we need to figure out all necessary experiment instruments and the activities involved.

Coding was performed by two researchers and inter-rater reliability of their results was determined using Cohen kappa, which showed a score: – 0.695. Students could receive one point for each inquiry stage that was placed appropriately in line with the stages before and after this particular stage (it was possible to collect a maximum of six points).

The improvement of the students' general inquiry knowledge was analysed with the non-parametric Wilcoxon signed-rank test, and relations between the general inquiry knowledge and transformative processes were assessed by Spearman's correlation. Non-parametric analyses were conducted because the results were assessed at an ordinal scale and did not conform to a normal distribution.

4. FINDINGS AND DISCUSSION

The following chapter discusses the results of three sub-studies (Papers I, II, III and IV) in the light of the theoretical framework of inquiry-based learning processes developed here. In order to construct the complete framework there was first a need to empirically investigate each of its components (transformative, regulative and inquiry meta-processes) separately. Therefore, sub-study I concentrated on the development of students' inquiry skills (see section 4.2.) according to an initial framework of inquiry-based learning processes (see section 4.1.); sub-study II specified the relations between different inquiry skills and inquiry-based learning processes (section 4.3.); and sub-study III identified the improvement of students' general inquiry knowledge in the context of inquiry-based learning processes (section 4.4.). Considering the results of the three sub-studies and the literature review involved, it was possible to improve the initially constructed theoretical framework of inquiry-based learning towards a revised version that integrates all inquiry-based learning processes (see section 4.5.). An additional outcome of the current study – inquiry learning environment Young Researcher that is designed for applying the framework proposed in the current study – is introduced in section 4.6. All empirical data was collected in out-of-school settings, but it is also discussed how the findings could be applied in classroom settings and even if not using a web-based learning environment.

4.1. Initial framework of inquiry-based learning processes

The initial framework of inquiry-based learning processes was constructed based on the inquiry cycle described by White and Frederiksen (1998, 2005, see section 2.2.1.), which integrates the regulation process of inquiry-based learning with transformative processes. The main difference from the cycle provided by White and Frederiksen is that it is hypothesized that regulative activities not only affect transformative processes (indicated as thick arrows) but furthermore affect themselves (indicated as thin double arrows) (see Figure 4). Research has shown that this kind of regulation of inquiry-based learning ensures meaningful and effective learning for the students (Hagemans, van der Meij, & de Jong, 2013; Manlove, Lazonder, & de Jong, 2009; Reid, Zhang, & Chen, 2003).

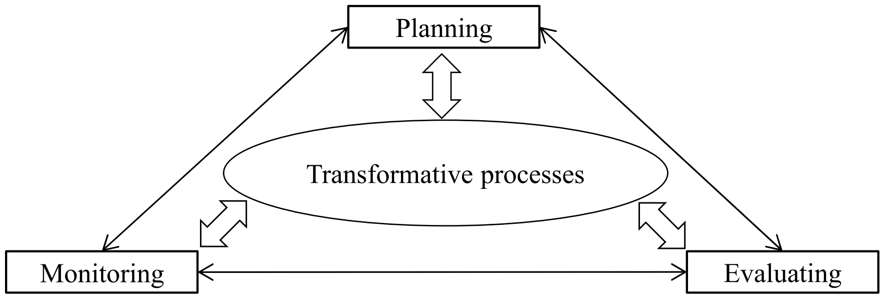

Figure 4. Initial framework of inquiry-based learning processes – Regulation of inquiry-based learning (see Paper II).

Regulative processes function to help students to plan all activities for transformative processes, to monitor and evaluate the success of the plan and, if necessary, to make some changes to the initial plan. De Jong et al. (2005) have demonstrated that the ability to regulate learning processes constitutes a key element of students' performance. However, it is not clear what the correct natural sequence of regulative activities in the learning process is. In most cases (de Jong & Njoo, 1992; Veermans, 2002), they have been presented in a linear sequence; but there is no significant reason to assume that earlier activities (Planning) must occur before later activities (Evaluating) (Azevedo, Moos, Johnson, & Chauncey, 2010). Thus (as demonstrated in Figure 4), evaluation could be followed by planning, and monitoring could be the first activity in the learning process.

In order to test the applicability of this framework, students' inquiry-based learning processes were studied empirically in applying the web-based inquiry learning environment Young Researcher in the context of an all-Estonian competition. According to the framework, first, the development of students' inquiry skills and, next, associations between inquiry-based learning processes were found.

4.2. Development of students' inquiry skills

The development of students' inquiry skills was investigated in sub-studies I and II (Papers II and III) through applying the web-based inquiry learning environment Young Researcher. However, the methods for evaluating transformative inquiry skills were already developed in an earlier study in another inquiry learning environment Young Scientist (Paper I). This learning environment was applied in classroom settings (Pedaste & Sarapuu, 2007) and, therefore, the findings of the current study could be considered to apply not only in out-of-school settings.

More specifically, in sub-study I, the aim was to identify the improvement of students' inquiry skills that corresponded to the transformative processes. In addition, one regulative process was investigated through asking each student to plan a transformative activity (students set goals, planned time needed for each activity, and made a plan for activities that they needed to undertake while, e.g., formulating their research questions) a transformative activity.

Therefore, the following items were assessed: the successfulness of research question formulation, hypothesis formulation, experiment planning; skills in analysing data and making conclusions; and the skill of planning, a regulative skill. This was also important for testing if the learning environment Young Researcher was suitable for studying different aspects in the framework of inquiry-based learning processes – if the learning environment did not improve students' inquiry skills, it could not be regarded as an inquiry learning environment and the processes of inquiry-based learning could not be studied.

The results showed a statistically significant improvement in all inquiry skills (see Table 1 in Paper II). The most developed transformative inquiry skills were skills of formulating research questions, hypotheses and conclusions. In addition, planning as a regulative skill was improved. This was a rather interesting result, because related research has stated that hypothesis formulation, for instance, was too difficult for students and thus, appropriate support was needed (Chinn & Brewer, 1993; de Jong and van Joolingen, 1998). To support students, possibilities were offered (as described in Paper II) whereby students could choose a suitable research question, hypothesis, and conclusions from a list. Providing students with the opportunity to select an appropriate hypothesis from a list helps to improve their skills of stating hypotheses (e.g., Michael, Haque, Rovick, & Evens, 1989). This finding can also be applied in the classroom or outside the web-based learning environment since even there it is possible to provide students with a list of research questions, hypotheses or conclusions that can be analysed during the inquiry-based learning process.

In sub-study II the improvement of the quality of students' regulative skills (see Table 2, Paper III) was investigated. The results showed that students' regulative skills were at a lower level than their transformative inquiry skills. The levels of planning and monitoring skills were almost equal (38% and 39%, respectively), while the evaluation skills were lower (30% from maximum). Thus, it was not possible to specifically identify the development of regulative skills and their sub-skills. But considering the summative effect of all regulative skills, it was possible to identify an improvement at the general level of regulative skills (see Table 2 in Paper III). Therefore, the improvement of evaluating ($Z=-4.6$; $p<0.001$), planning ($Z=-3.3$; $p<0.001$), and monitoring ($Z=-2.6$; $p<0.001$) was statistically significant. However, the summative effect of all regulative skills revealed that there was quite a low number of student pairs who stayed at the same level when comparing the results of their pre- and post-task. What was their actual level of a particular regulative inquiry process was not investigated. Only hypothetical reasons are possible, but this needs further investigation. The focus was only on detecting positive and negative changes. According to this, 25 pairs out of 42 improved their results in planning, 30 pairs in evaluating and 24 in monitoring.

4.3. Associations between processes of inquiry-based learning

Associations between inquiry-based learning processes were found in both sub-study I and II. Specifically, the purpose of sub-study I was to detect relations between the development of transformative inquiry skills and regulative inquiry skills (Figure 4 in Paper II) and between particular regulative skills (Figure 4 in Paper III). Spearman correlation coefficients were calculated in order to describe the theoretical framework of the regulation of inquiry-based learning, which was outlined first in Paper II, but further developed and analysed in Paper III.

The results presented in Paper II showed only one positive significant correlation between regulative and transformative inquiry skills (see Figure 4, Paper II). The correlation between planning and transformative inquiry skills was 0.584 ($p<0.001$). This correlative relation was expected, as effective planning has been shown to be a key prerequisite for success in transformative inquiry processes. However, unexpectedly, no remarkable correlations were found between any other regulative processes and transformative processes. This can be hypothetically explained as being the result of the low quality of monitoring and evaluation. This could also be a reason why the activity level of these processes did not decrease throughout the learning process. The decrease in the activity level should theoretically be dependent on an increase in the level of quality and automatization. If the level of the quality of the processes is high, they can be automated and there is no longer a need to focus on these areas. This discussion point should be addressed in future studies in which both the quality and activity levels of all regulative inquiry processes can be assessed. It was also found that particular regulative inquiry skills do not significantly relate to each other. This means that the activity level of monitoring does not correlate with either the activity level of evaluation or the quality of planning.

The same was true for all combinations of regulative processes. One possible explanation for this outcome is that the students were planning, monitoring or evaluating their learning processes occasionally, but not in a systematic way – some students sometimes planned their studies, but did not pay attention to monitoring and evaluation, while other students focused on monitoring or evaluation, but did not plan their studies carefully. This demonstrated that there was a critical need for resources to guide students towards coherent regulation, in which planning was taken into account in monitoring and evaluation, and monitoring and evaluation provided essential input for successful planning.

Considering the results of sub-study I, sub-study II was designed. Based on the findings of Paper II, additional supportive elements were added to the learning environment Young Researcher; also, questions for assessing regulative inquiry skills were improved (see Paper III, and section 3.2.). It was important to further investigate the initial framework of inquiry-based learning processes.

The results of sub-study II revealed that the higher the level of regulative skills, the higher the level of transformative inquiry skills. Thus, compared to sub-study II, the results of sub-study III showed a significant correlation between all regulative inquiry processes and transformative inquiry skills (see Figure 3 in Paper III). The regulative inquiry skill of evaluating had the strongest correlation with transformative inquiry skills ($\rho=0.572$; $p<0.001$). Also, it was identified that all regulative inquiry skills were strongly and significantly related to each other. The strongest correlation was found between planning and monitoring ($\rho=0.877$; $p<0.001$). These results support the claim that the success of inquiry-based learning processes depends on effective regulation (as shown by de Jong et al., 2005), and also demonstrate that while designing one inquiry-based task with appropriate supportive activities for one transformative or regulative inquiry process, improvement in all inquiry skills related to the other processes can be expected, as well (see Paper III).

In conclusion, it was found that all regulative inquiry skills were correlated with transformative inquiry skills. However, more information was needed on how to positively affect inquiry-based learning processes, since the regulative inquiry skills were not at a very high level (see section 4.2.). It was considered that a more general understanding about the importance and relations of inquiry-based learning processes was needed. That led to the search of general inquiry knowledge which could activate inquiry meta-processes to guide the whole inquiry-based learning.

4.4. Improvement of students' general inquiry knowledge

Sub-study III was designed based on a revised framework of inquiry-based learning processes. In this case inquiry meta-processes (see section 2.2.4) and related general inquiry knowledge were integrated to the framework. In empirical data collection student pairs' general inquiry knowledge was evaluated by applying the web-based inquiry learning environment Young Researcher in an all-Estonian competition. Specifically, this meant assessing the participants' knowledge about transformative inquiry stages and their necessity for inquiry-based learning (see Paper IV, Table 3). Sixty-five pairs who participated in the study showed a significant improvement ($Z=-2.2$; $p<0.05$) in sequencing transformative inquiry stages as they should be passed through while conducting inquiry-based learning.

Although the average score of students' general inquiry knowledge was quite high (4.5 out of 6.0) already in the pre-task, there were still 20 pairs out of 65 who showed positive improvement in sequencing inquiry stages (Paper IV, Table 3). There were also 10 pairs whose results in sequencing showed a negative change. The reason may be explained by the fact that it was a competition situation, and their overall position in the competition might have a negative effect on their motivation in answering the post-task. If they do not have much to win in the end, their motivation to complete the final task might be lower compared to the motivation of completing the first task, where there are no differences yet in the scores of the teams. It is important to note that the Wilcoxon sign test used to detect the change in students' general inquiry knowledge did not reveal any information about these 35 student pairs who stayed at the same level. Thus, this conclusion is made based on the results of 30 student pairs.

The most common mistake made in the pre-task was to mix up research question formulation with hypothesis formulation; however, in the post-task, they were placed in the correct sequence. This information can also be taken into account when designing inquiry-based learning in classroom settings or outside a web-based learning environment in general. In addition, it was also common for student pairs to start with experiment planning, which is somewhat justified, since in typical school situations, the science class students often start their inquiry-based learning by planning. The aim was to broaden students' knowledge about inquiry-based learning by presenting the list of inquiry stages in the pre-defined order. Of course, it can be criticized by the fact that scientists do not actually work in that way, but students benefit if they have an idea what is behind inquiry-based learning. The same can be suggested in classroom settings, where inquiry-based learning should start from formulating research questions, not from hypothesizing or planning, or even from applying a pre-defined plan like a cookbook.

Under general inquiry knowledge, student pairs' knowledge about the necessity of each transformative inquiry process was also assessed. A significant development was detected in the students' explanations about the necessity of each transformative process. The biggest differences appeared in explaining the necessity of research question formulation and drawing conclusions (see Table 3 in Paper IV). Students explained that without a question to investigate it is impossible to start an inquiry-based learning, and the question is what needs to be answered through the inquiry-based learning. Drawing conclusions was stated in the pre-task to be just conclusions about what has been done, but in the post-task students added that it is an answer to the research question and is therefore also the answer to the problem. In addition, positive improvements were found in the explanations about hypothesis formulation, carrying out an experiment, and analysis of data. But no statistically significant improvement was found in the necessity of experiment planning. Here 36 out of the 65 pairs stayed at the same level in their explanations. However, the mean scores of the pre- and post-tasks showed a slight positive change (from 1.8 to 2.0).

In general, the results indicate that the application of Young Researcher supported the development of the student pairs' general inquiry knowledge (Paper IV). In the learning environment, the pairs were put into a learning situation where an appropriate sequence of transformative processes was given, and knowledge of the necessity of the particular stages was only supported by their practice or optional guidance provided by the virtual professor. There were no specific assignments for supporting the development of students' general inquiry knowledge, e.g., tasks for analysing why a research question should be formulated before formulating a hypothesis or why a hypothesis is needed at all in the process of inquiry-based learning. However, despite the specific support, an improvement of general inquiry knowledge was demonstrated and the same could be expected when applying a similar design of inquiry-based learning in classroom settings in a real learning environment.

4.5. Revised theoretical framework of inquiry-based learning processes

As the main outcome of the current study, a theoretical framework of inquiry-based learning processes was constructed (see Figure 5). It was derived from the initial framework (see section 4.1.) that was revised according to the empirical studies and considering the literature review of inquiry meta-processes. In this framework the role of general inquiry knowledge in enhancing students' inquiry skills should be emphasized, as it has not been studied in previous studies and would add significant new knowledge to the theoretical framework of inquiry-based learning processes. The framework presents the entire inquiry-based learning process, demonstrating flows of inquiry-based learning processes and relations between them (input from Papers II and III). According to the framework, inquiry-based learning takes place through three inquiry-based learning processes: (a) inquiry meta-processes, (b) transformative processes, and (c) regulative processes (Paper IV).

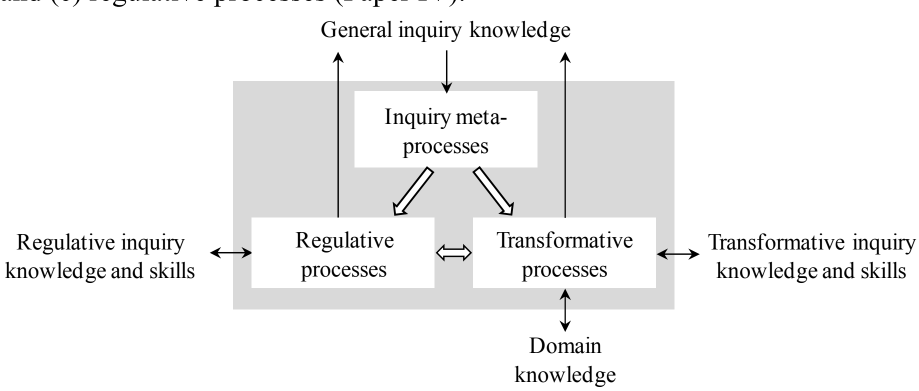

Figure 5. The theoretical framework of inquiry-based learning processes developed in the current study: (a) processes involved in the inquiry-based learning process (grey area), (b) relations between processes (thick arrows), and (c) relations between knowledge and skills related to the inquiry-based learning processes (thin arrows). The direction of the arrows indicates information flows between different components of the framework (Paper IV).

The starting point of this framework of inquiry-based learning processes is in the general inquiry knowledge by which inquiry meta-processes are activated. Meta-processes are needed to plan a general course of regulative and transformative processes to achieve their coherence. Regulative and transformative processes, however, are also in relation to each other (empirically tested in sub-study I and II). According to the theoretical framework, regulative processes support transformative processes through the activities of planning, monitoring, and evaluating. At the same time, transformative processes give input for applying regulative processes (needs empirical testing in further studies). If a learner has reached a result in a particular inquiry stage, the outcome should be evaluated. This evaluation is a regulation process that emerges from the result of a transformative process. All these processes require specific knowledge and, sometimes, skills. Meta-processes require general inquiry knowledge; regulative processes are based on regulative inquiry knowledge and skills (needs empirical testing in further studies); and transformative processes rely on transformative inquiry knowledge and skills (empirically tested in sub-study III). Regulative processes need declarative knowledge (e.g., monitoring is necessary) and procedural knowledge (e.g., activities involved with monitoring) (Veenman & Verheij, 2001). Transformative processes also need declarative knowledge (e.g., a research question is necessary) and procedural knowledge (e.g., activities necessary for research question formulation). According to the theoretical framework of inquiry-based learning processes, these two types of knowledge are related to general inquiry knowledge.

In addition, transformative processes need some input from domain-related knowledge (conceptual knowledge), while regulative and meta-processes are more general and are based on knowledge that is not domain-dependent, and can be transferred from one context to another without specific limitations (needs empirical testing in the studies). According to this framework, general inquiry knowledge is a prerequisite for the acquisition of specific knowledge and skills that are necessary for transformative and regulative processes.

Regulative and transformative processes are associated with particular knowledge and skills by two-directional arrows (Paper III). Consequently, these types of knowledge and skills are needed to conduct these processes, but performing the processes also improves them. An exception can be seen in the case of meta-processes, as knowledge applied in them will be evaluated through regulative and transformative processes. Thus, an improvement in general inquiry knowledge can be expected if learners perform regulative or transformative processes successfully. Therefore, there are one-way arrows from general inquiry knowledge towards meta-processes, and the same from regulative and transformative processes towards general inquiry knowledge.

In conclusion, the revised framework of inquiry-based learning processes has been developed based on theoretical justification and partly tested empirically in a web-based inquiry learning environment in out-of-school settings.

However, as most of its theoretical underpinning is not specific to either web-based learning environments or out-of-school or classroom settings it could be considered for a wide implementation in designing inquiry-based learning.

4.6. The learning environment Young Researcher

In order to test the initial theoretical framework of inquiry-based learning empirically and to improve it based on empirical data it was embedded in a web-based learning environment. In this study, the inquiry learning environment Young Researcher (http://bio.edu.ee/teadlane/) was applied, which is designed for students to learn biology topics (*"Why is it hard to catch a falling body?", "Why do our pulse and breathing rate change?", "Why do muscles wear down differently?", "Why does extra weight accumulate?", and "Why do organisms need water?"*). These topics are associated with the Estonian science curriculum (Mäeots et al., 2009).

Each task in the learning environment is structured according to the inquiry stages: problem identification; research question and hypothesis formulation; experiment planning; carrying out an experiment; analysis and interpretation of results; and drawing conclusions (Mäeots et al., 2009). In the case of experiments, three out of five are real experiments and need at least two students. Tasks are designed so that solving one task takes 45 minutes (one school lesson in Estonia). Thus, teachers can easily apply the learning environment in their lessons. The learning environment needs internet connection, but it does not necessarily require a computer lab.

The learning process is guided by a virtual teacher (see Appendix 2). Students interact with the virtual teacher during the entire learning process. Although students state their own questions, it always follows the problem that was presented by the virtual teacher. In general, students' real teacher is passive and is essential only at the start of the lesson (helping to log in to the learning environment and to choose the correct task) and at the end of the lesson (giving general feedback and conducting the evaluation process in the form of marks).

To help students in their learning, different forms of supportive elements are offered by the Young Researcher learning environment. In preparing appropriate supportive elements, previous experience with a similar learning environment Young Scientist was considered (Paper I).

Effective scaffolding needs to be distributed, integrated, and multiplied so that students have more opportunities to notice and take advantage of the affordances of the environment and activity (Puntambekar & Hübscher, 2005). The content of these elements is designed to account for the characteristics of general inquiry knowledge, as well as transformative and regulative processes (see Appendix 3). Some of these elements are designed to support one specific type of inquiry knowledge and skills, but most of them can be flexibly applied for supporting different types of knowledge and skills, e.g., students' general inquiry knowledge and transformative inquiry knowledge, and the skills that are supported by a *Virtual professor*, *Virtual teacher* and *Virtual blackboard* (Paper IV).

On the basis of the definition of general inquiry knowledge applied in this study, the following aspects of general inquiry knowledge were considered while designing the supportive elements:

- In order to understand the inquiry-based learning process as a whole, the presence of a pre-defined order of inquiry stages was necessary throughout the learning process. This information was presented on the *Virtual blackboard*.
- Guidelines for presenting the relations between the stages, and for explaining the necessity of each stage in the context of the whole inquiry-based learning, were also necessary. This was provided through designing the texts of the *Virtual teacher and Professor.*

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The aim of the current study was to construct a revised theoretical framework of inquiry-based learning processes that considers three processes – transformative, regulative, and inquiry meta-processes – and shows how these processes are related to each other. Some of these relations were studied empirically, while the others were justified theoretically (see section 4.5.). The essence of this framework was embedded to the learning environment Young Researcher, which followed the theoretical concept of the framework. All empirical evidence was collected in the Young Researcher learning environment.

The construction of the framework started from the review of literature. As a result of it, a framework of relating transformative inquiry skills and regulative inquiry skills was developed. In this framework all regulative inquiry processes were related to transformative inquiry processes. In addition, relations were specified between each of the regulative processes.

In the second phase, this framework was tested empirically in web-based out-of-school competition settings. Two sub-goals set for empirical studies were approached. In sub-study I, the development of students' inquiry skills was clarified. It was shown that there was a statistically significant development of transformative inquiry skills; however, no increase in regulative inquiry skills was detected. Also, no correlation was revealed between inquiry skills. In sub-study II, the learning environment was improved and, as a result, development of regulative inquiry skills was detected. It enabled to focus on specifying the correlations between different inquiry skills and inquiry-based learning processes. In this case all regulative inquiry skills correlated statistically significantly and positively with transformative skills. However, the regulative inquiry skills were not at a very high level and there was a need to define a process to affect inquiry-based learning processes as a whole. This was done in the context of the third phase of the study.

The third phase of the study was for revising the framework of inquiry-based learning processes by adding the concept of inquiry meta-processes and related general inquiry knowledge. It was argued, based on the literature review, that inquiry-based learning should start from general inquiry knowledge that activates inquiry meta-processes, which are needed to guide the transformative and regulative inquiry processes. The relation between general inquiry knowledge and regulative inquiry processes was not tested but the correlation between general inquiry knowledge and transformative inquiry skills was revealed in empirical studies. It was the main outcome of sub-study III that also helped to discover the improvement of students' general inquiry knowledge.

More specifically, sub-studies I, II and III were suitable for answering three general research questions addressed in the current study:

- The learning environment Young Researcher that was designed to support the initial framework of inquiry-based learning processes was suitable for developing students' transformative and regulative inquiry skills.
- It revealed that different regulative inquiry skills – planning, monitoring, evaluating – correlate strongly with each other. The correlation between particular regulative skills and transformative skills is moderate but still statistically significant.
- The learning environment Young Researcher that was updated according to the revised framework of inquiry-based learning processes was applicable for improving students' general inquiry knowledge.

Thus, the empirical outcomes of the study also support the theoretical framework of inquiry-based learning processes. The findings of this study could be applied by teachers, who could consider the design of the learning environment of the inquiry-based learning process even in classroom settings and not only in web-based learning environments. It is especially important to consider that general inquiry knowledge is needed to activate transformative inquiry processes.

5.2. Recommendations

Based on the theoretical and empirical findings of the current study several recommendations can be made to researchers, teachers and designers of learning environments. As the theoretical basis for the framework of inquiry-based learning processes is not bind to either out-of-school settings or web-based learning environments (where were conducted related empirical studies) these can be also considered for applying in classroom settings.

For researchers:

- to find out how to support different inquiry-based learning processes more effectively, regulative inquiry processes of inquiry-based learning should be considered;
- to find out how to assess the quality and activity levels of all regulative inquiry processes more effectively, instruments that can be applied in other studies as well have been developed in this study and it is recommended to re-use them in other studies;
- to set the criteria for an effective scaffold to be used to support the development of students' transformative and regulative inquiry skills as well as general inquiry knowledge should be supported.

For teachers:

- teachers who are starting inquiry-based learning with students should ensure that the students have the general inquiry knowledge at a level that is sufficient for starting with inquiry-based learning;
- teachers should promote regulative activities more while implementing inquiry-based learning in their class;
- as the results of the current study showed, it is recommended to implement the learning environment Young Researcher for learning biology through inquiry-based learning.

For designers of learning environments:

- in designing inquiry learning environments, aspects of all three inquiry-based learning processes – transformative, regulative and inquiry meta-processes – should be considered.

6. LIMITATIONS

Considering the design and the results of the current study, limitations which leave room for future research can be pointed out. The main limitations are the following:

- All the data was collected during inquiry learning competitions, where students could solve tasks in their place of choice (e.g., at home). This reduced control over the students' actual activities. In addition, it means that the sample of the studies might not be representing an average student because most of the students who started to use the learning environments were highly motivated.
- Even though the competition attracted lots of students to participate, the number of students who finished the competition on time was mostly around 50%. We have not analysed the data of these students because, in this case, only partial data is available. However, it could be hypothesized that the learning process of these students is different from those who completed their competition on time.
- The competition format did not allow the evaluation of all the regulative skills that are presented in Table 1. Thus, a more specific instrument should be developed and tested in further studies.
- The constructed framework of inquiry-based learning processes has not been empirically tested in its entirety. Therefore, there is a need for future studies in order to identify all the relations that the developed framework represents.

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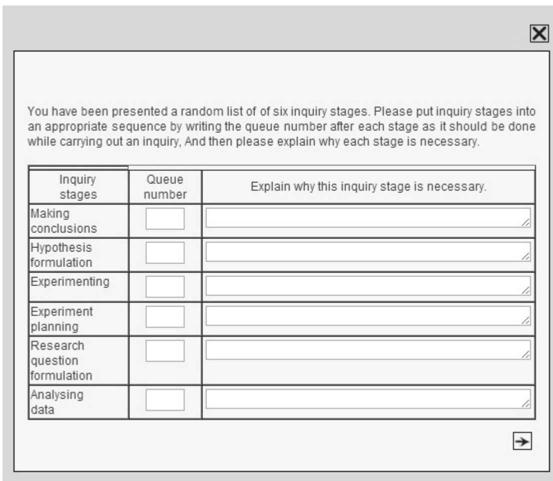
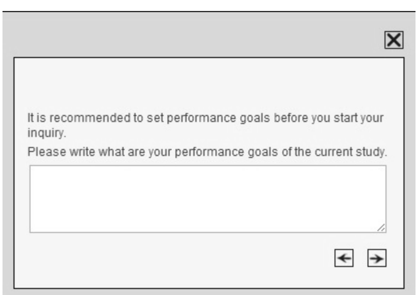
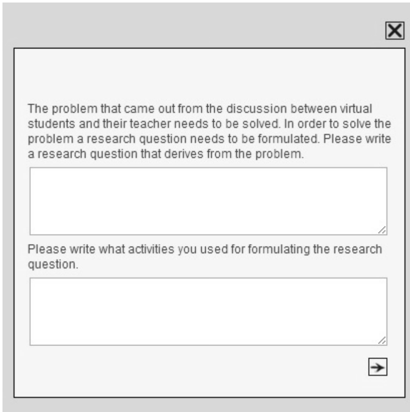
APPENDICES

Appendix 1. Tasks in the learning environment Young Researcher for evaluating particular inquiry-based learning processes.

Task number	**Screenshot of the task**	**Explanation**
1		**Task:** Students have to sequence transformative inquiry processes and explain why each process is necessary. Processes are listed in random order: making conclusions, hypothesis formulation, experimenting, experiment planning, research question formulation, analysis of data. **Task aims to evaluate:** general inquiry knowledge. **Assessment:** see table 2**.** **Answer type:** open-ended.
2		**Task:** Students have to set their performance goals considering the problem they are going to solve. **Task aims to evaluate:** regulative planning skill. **Assessment:** 0 points – goal is not set 1 point – goal is set but is not considering the problem 2 points – performance goals consider the study problem **Answer type:** open-ended.

3		**Task:** Based on the real-life story that is presented by virtual students and their teacher, students have to formulate a research question and after that they have to explain what activities they used in order to formulate this research question. **Task aims to evaluate:** research question formulation skill and regulative planning skills **Assessment** (research question)**:** *Formulation of the research question:* 0 points – question is not formulated 1 point – question does not derive from the problem 2 points – question derives from the problem *Correctness of the dependent variable:* 0 points – no dependent variable 1 point – wrong dependent variable (does not derive from the problem) 2 points – correct dependent variable that derives from the problem *Correctness of the independent variable:* 0 points – no independent variable 1 point – wrong independent variable (does not derive from the problem) 2 points – correct independent variable that derives from the problem **Assessment** (regulative planning skills)**:** 0 points – there is no description of their planning activities 1 point – activities are described at a general level 2 points – activities are described in detail **Answer type:** open-ended.

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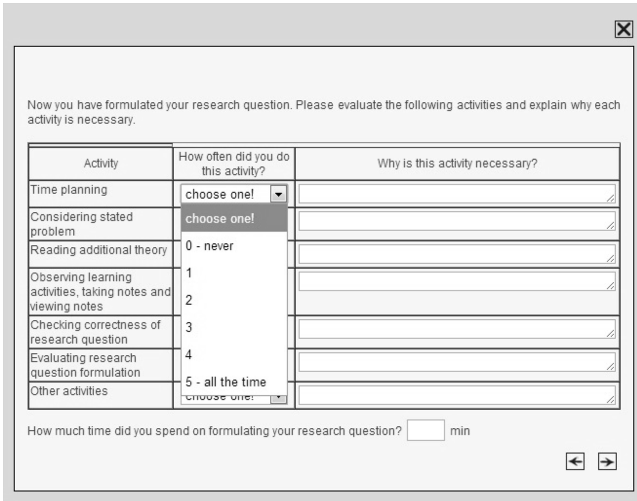

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<td>
Task: After the students have formulated their research question they have to evaluate activities that are given in a pre-defined list. The activities consider the concept of regulative skills as presented in Table 1. Pre-defined list: time planning, considering the problem, reading additional theory, observing learning activities, taking and viewing notes, checking the correctness of the research question, evaluating the research question, other activities. For each activity students have to explain why it is necessary. Also, using Likert scale, students have to evaluate how often they used a particular activity.
Task aims to evaluate: activities common for monitoring and evaluating.
Assessment (necessity of each activity):
0 points – necessity of activity is not explained
1 point – necessity of activity is explained at a general level
2 points – necessity of activity is explained in detail
Answer type: open-ended, choose from the list.
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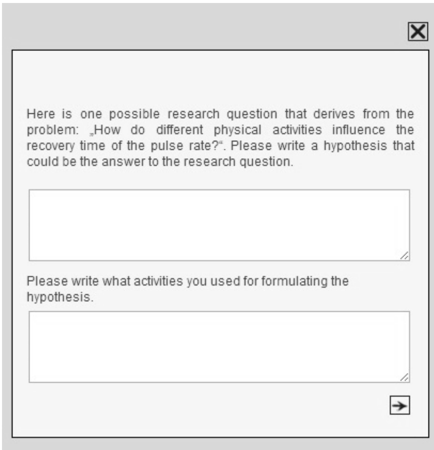
5		**Task:** Based on the formulated research question, students have to formulate a correct hypothesis. In order to help the students, one possible research question is given as an example. **Task aims to evaluate:** hypothesis formulation skill. **Assessment** (hypothesis formulation)**:** *Formulation of the hypothesis:* 0 points – hypothesis is not formulated 1 point – hypothesis does not derive from the research question 2 points – hypothesis derives from the research question *Correctness of the dependent variable:* 0 points – no dependent variable 1 point – wrong dependent variable (does not derive from the problem) 2 points – correct dependent variable that derives from the problem *Correctness of the independent variable:* 0 points – no independent variable 1 point – wrong independent variable (does not derive from the problem) 2 points – correct independent variable that derives from the problem *Correctness of the relations between independent and dependent variables:* 0 points – relation is missing 1 point – relation is not considering the problem and/or research question 2 points – relation considers the problem and/or research question, but is not accurate 3 points – relation considers the problem and research question and is theoretically accurate **Assessment** (regulative planning skills)**:** 0 points – there is no description of their planning activities 1 point – activities are described at a general level 2 points – activities are described in detail **Answer type:** open-ended.

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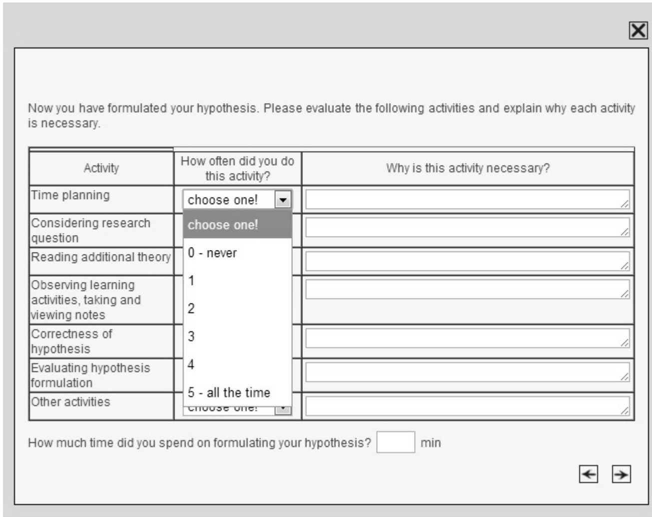

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<td>
Task: Similarly to the research question students have to evaluate their activities after they have formulated their hypothesis. Pre-defined list: time planning, considering the research question, reading additional theory, observing learning activities, taking and viewing notes, checking the correctness of the hypothesis, evaluating the hypothesis, other activities. For each activity students have to explain why it is necessary. Also, using the Likert scale, students have to evaluate how often they used a particular activity.

Task aims to evaluate: activities common for monitoring and evaluating.

Assessment (necessity of each activity):
0 points – necessity of activity is not explained
1 point – necessity of activity is explained at a general level
2 points – necessity of activity is explained in detail

Answer type: open-ended, choose from the list.
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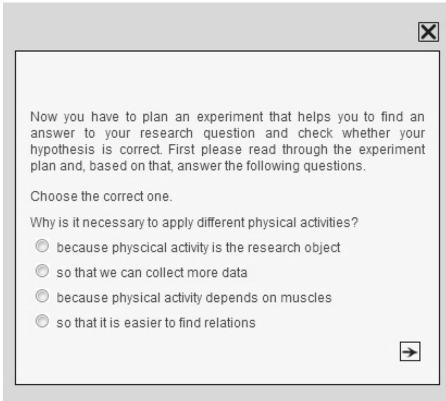
<td>
</td>
<td> Task: Students have to read the experiment plan that is provided by the learning environment Young Researcher. Based on the experiment plan students are asked to answer three questions about the plan: “Why is it necessary to apply different physical activities?”; “Why do you have to set detailed experiment conditions?”; “Why do you have to consider the safety aspect during the experiment?”.
Task aims to evaluate: understanding the experiment plan.
Answer type: open-ended, choose from the list. </td>
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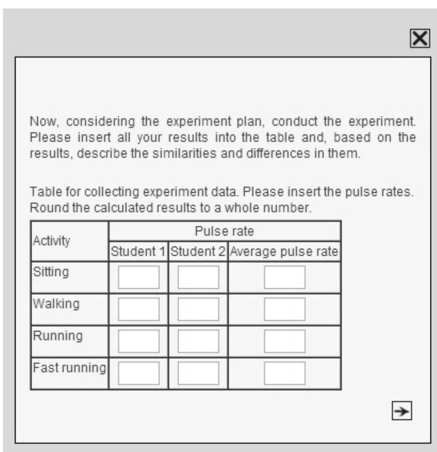
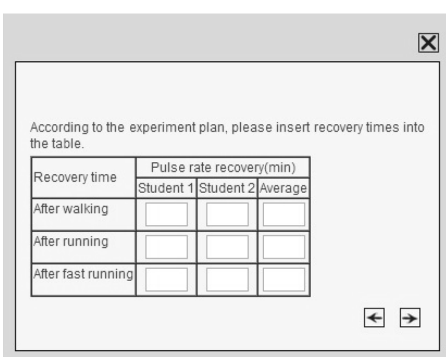
<td>8</td>
<td>


</td>
<td> Task: Based on the experiment plan students conduct the experiment. All results are added to the table. Depending on the content students carry out a real or virtual experiment (see section 4.5.).
Task aims to evaluate: accuracy of experimenting.
Assessment:
0 points – table is not filled in or is filled in using meaningless or random numbers or letters
1 point – table is filled in with numbers but data only partially derives from the experiment
2 points – table is filled in with numbers and data from the experiment
Answer type: open-ended. </td>
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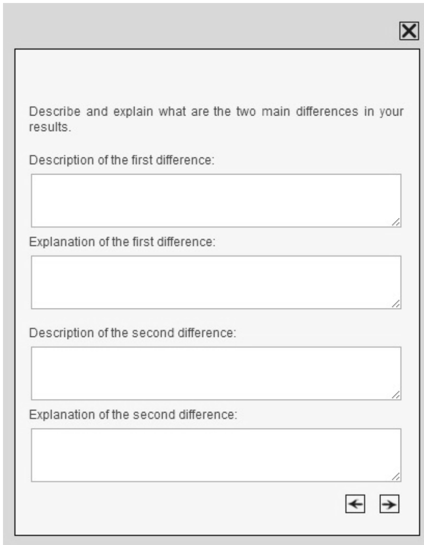
9



Task: Students have to describe and explain what differences occurred among their results. Students make an initial analysis of the data.

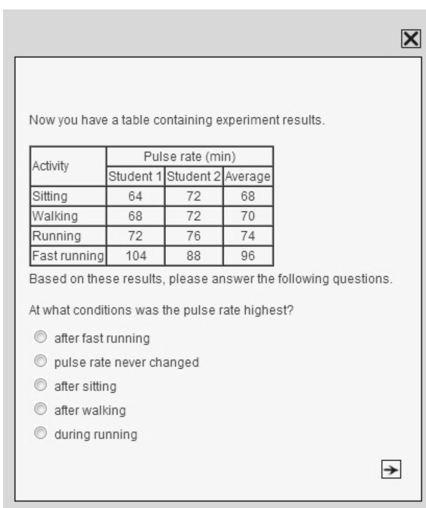
Task aims to evaluate: data analysis skills.

Assessment (differences):
0 points – no difference is described
1 point – difference is described but does not derive from data
2 points – difference is described and derives from data

Assessment (explanation):
0 points – no explanation about the difference is given
1 point – difference is explained at a general level
2 points – difference is explained in detail

Answer type: open-ended.

10

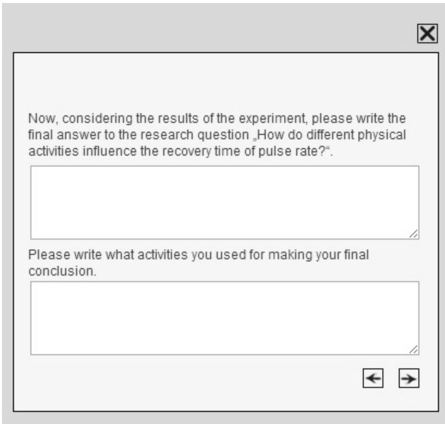


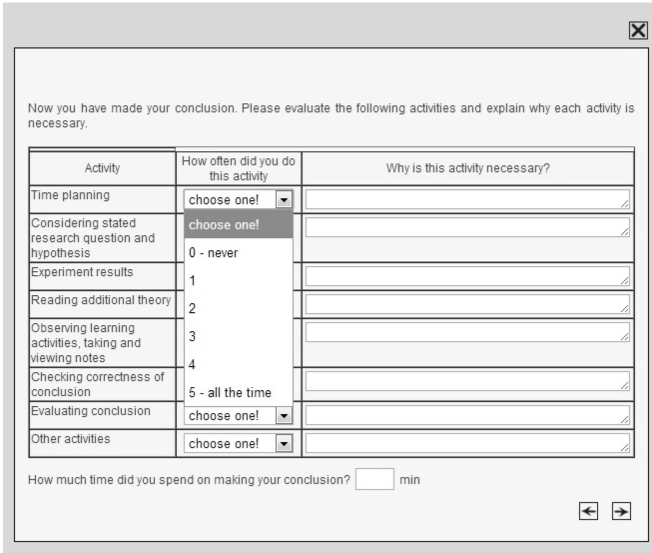
Task: After analysing their own results students are given results of the control experiment made by the authors of the learning environment. Based on the predetermined table students have to analyse the data by answering questions about the results: e.g., "At what conditions was the pulse rate highest?"; "At what conditions was the recovery time shortest?".

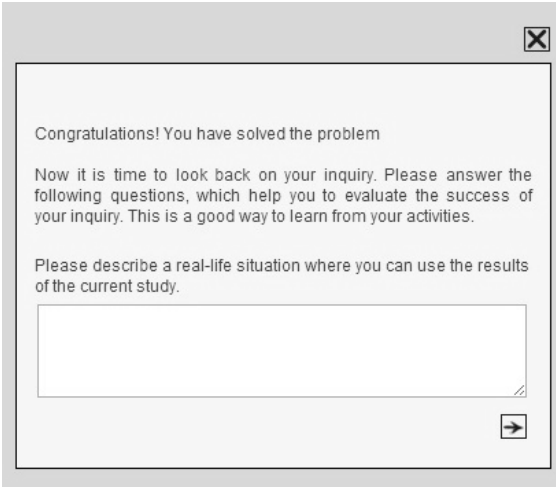
Task aims to evaluate: data analysis skills.

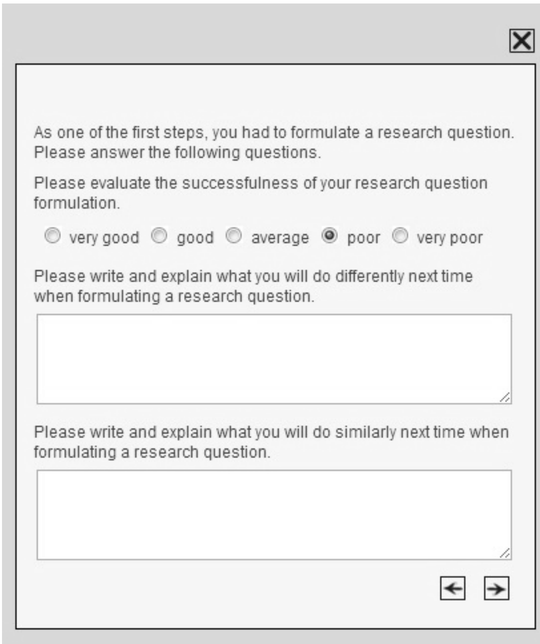
Assessment:
0 points – wrong answer
1 point – correct answer

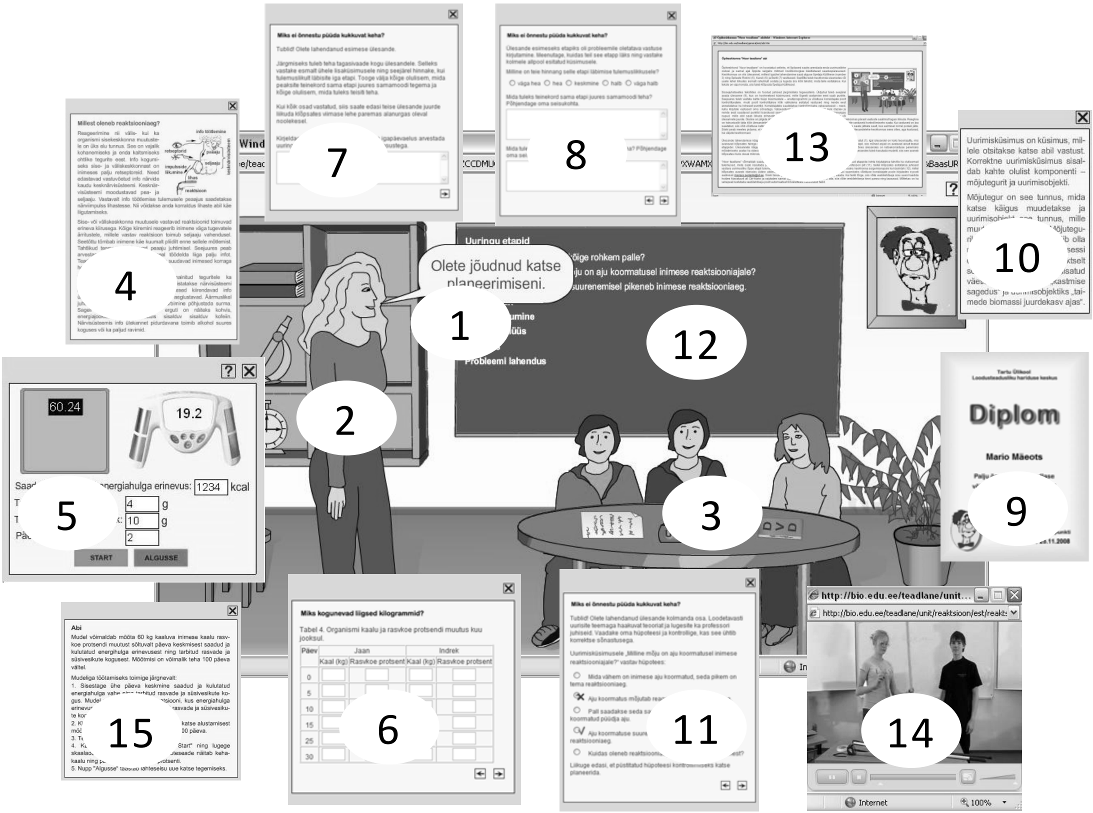
Answer type: multiple-choice.

11		**Task:** After analysing the data students have to formulate the final conclusion that answers the formulated research question. **Task aims to evaluate:** conclusion making skills. **Assessment** (making a conclusion)**:** *Formulation of the conclusion:* 0 points – conclusion is not formulated 1 point – conclusion does not derive from the research question 2 points – conclusion derives from the research question *Correctness of the dependent variable:* 0 points – no dependent variable 1 point – wrong dependent variable (does not derive from the problem) 2 points – correct dependent variable that derives from the problem *Correctness of the independent variable:* 0 points – no independent variable 1 point – wrong independent variable (does not derive from the problem) 2 points – correct independent variable that derives from the problem *Correctness of the relations between independent and dependent variables:* 0 points – relation is missing 1 point – relation is not considering the results of the study and/or research question 2 points – relation considers the results of the study and/or research question, but is not accurate 3 points – relation considers the research question and is in accordance with the results of the study **Assessment** (regulative planning skills)**:** 0 points – no description is given about their planning activities 1 point – activities are described at a general level 2 points – activities are described in detail **Answer type:** open-ended.

12		**Task:** Similarly to the research question and hypothesis formulation students have to evaluate their activities after they have made their conclusion. Pre-defined list: time planning, considering research question and hypothesis, experiment results, observing learning activities, taking and viewing notes, checking the correctness of the conclusion, evaluating conclusion, other activities. For each activity students have to explain why it is necessary. Also, students have to evaluate, using Likert scale, how often they used a particular activity. **Task aims to evaluate:** activities common for monitoring and evaluating. **Assessment** (necessity of each activity): 0 points – necessity of activity is not explained 1 point – necessity of activity is explained at a general level 2 points – necessity of activity is explained in detail **Answer type:** open-ended, choose from the list.

13		**Task:** Students have to think of a real-life situation where the results of the study can be used. **Task aims to evaluate:** evaluating sub-skill reflection (applying obtained knowledge for future studies). **Assessment:** 0 points – situation is not described 1 point – situation is described, but is not considering the results of the study 2 points – situation is described and considers the results of the study **Answer type:** open-ended.

14		**Task:** Students have to reflect on their learning by evaluating the successes of each transformative process (e.g., research question formulation). First students evaluate their successfulness by using the 5-point Likert scale. After that they have to explain what they will do differently next time and what they will do similarly next time when they, e.g., formulate a research question. **Assessment** (next time differently): 0 points – no difference is described 1 point – difference is described, but is not considering the inquiry stage (e.g., research question) 2 points – difference is described and considers the inquiry stage **Assessment** (next time similarly): 0 points – no similarity is described 1 point – similarity is described, but is not considering the inquiry stage (e.g., research question) 2 points – similarity is described and considers the inquiry stage **Answer type:** open-ended, multiple-choice



Appendix 2. The structure of the learning environment Young Researcher (Mäeots et al., 2009).

1 – a problem situation presented as text-prompts, 2 – a virtual teacher, 3 – virtual students, 4 – theoretical background about the process under investigation, 5 – a virtual tool for data collection, 6 – a table for data, 7 – a task for applying the solution of the problem in a new situation, 8 – a reflective generalization on the learning process, 9 – a diploma given at the end of the inquiry-based learning, 10 – the professor's guidelines for completing the inquiry stage, 11 – feedback given after completing each inquiry stage, 12 – a virtual blackboard presenting the inquiry stages, 13 – general technical help for using the learning environment, 14 – a video clip about how to carry out the experiment, 15 – a specific help page for using the electronic tools.

Appendix 3. Supportive elements in the learning environment Young Researcher, and how different types of knowledge and skills are supported through them (Paper IV).

Supportive element	**How different types of knowledge and skills are supported through elements**		
	General inquiry knowledge	**Transformative inquiry knowledge and skills**	**Regulative inquiry knowledge and skills**
Guidelines given by the *Virtual professor*	*Necessity of the stage:* e.g., hypothesis is the answer to the research question, which is theoretically justified and evaluated by an experiment.	*Components of the transformative process:* e.g., a research question is a question that contains independent and dependent variables.	*Evaluation of the learning process:* e.g., you have to check whether all components of the hypothesis are present and if it fits with the stated research question.
Guidelines given by the *Virtual teacher*	*Stage position in relation to other stages:* e.g., before conducting an experiment, scientists often formulate a hypothesis.		*Planning the learning process:* e.g., now you have to think how to check the correctness of the hypothesis.
Inquiry stage presented on the *Virtual blackboard*	*Stages in pre-defined sequence*: research question formulation, hypothesis formulation, experiment planning, carrying out an experiment, analysis of data, and drawing conclusions.	*Components of a transformative process*: after each stage, the correct answers appear on the blackboard next to the name of a particular stage (e.g., the correct hypothesis).	

SUMMARY IN ESTONIAN

Uurimuslik õpe veebipõhises õpikeskkonnas: uurimusliku õppe protsesside teoreetiline raamistik

Käesoleva doktoritöö eesmärgiks oli välja arendada uurimusliku õppe protsesside raamistik, mis võtaks arvesse uurimusliku õppega seotud transformatiivsed, regulatiivsed ja uurimuslikud metaprotsessid ning tooks välja nendevahelised seosed. Raamistiku esialgne versioon koostati tuginedes uurimusliku õppe tsükleid käsitlevale teaduskirjandusele. Seejärel koostati raamistiku alusel uurimuslik õpikeskkond „Noor teadlane“ ja testiti raamistiku kehtivust selles. Lisaks leiti kinnitus sellele, et kasutatud keskkond võimaldab arendada uurimuslikke oskusi. Samas ilmnes, et esialgne raamistik vajab edasiarendamist, ning sellesse integreeriti uurimuslikud metaprotsessid ja nendeks vajalikud uurimusliku õppe üldteadmised. Kokkuvõttes võib raamistiku koostamises eristada kolm etappi: 1) esialgse raamistiku koostamine kirjanduse alusel, 2) raamistiku rakendamine õpikeskkonna „Noor teadlane“ arendamisel ja testimine empiiriliselt, 3) raamistiku edasiarendamine ja täiendav testimine uurimuslikus õpikeskkonnas „Noor teadlane“.

Uurimusliku õppe protsesside esialgse teoreetilise raamistiku aluseks oli peamiselt White'i ja Frederikseni (1998, 2005) uurimusliku õppe tsükkel. Selle alusel eristati transformatiivsed ja regulatiivsed uurimuslikud protsessid. Erinevalt White'i ja Frederikseni tööst seoti käesolevas töös omavahel nii transformatiivsed ja regulatiivsed uurimuslikud protsessid kui ka erinevad transformatiivsed protsessid: planeerimine, jälgimine ja hindamine. Koostatud raamistiku kohaselt olid kõik regulatiivsed ja transformatiivsed protsessid omavahel kahesuunalises seoses – iga regulatiivne protsess võib olla korrelatiivses seoses transformatiivsete protsessidega ja ka iga regulatiivse protsessiga.

Järgmiseks testiti koostatud teoreetilist raamistikku empiiriliselt. Selleks arendati välja veebipõhine uurimuslik õpikeskkond “Noor teadlane” (http://bio.edu.ee/teadlane/), mille rakendamisel kahes alauuringus koolivälise võistlusena leiti vastused doktoritöö kahele alaeesmärgile. Esimeses alauuringus saadi kinnitust, et koostatud õpikeskkond arendab õpilaste transformatiivseid uurimuslikke oskusi. Samas õpilaste regulatiivsed uurimuslikud oskused ei arenenud statistiliselt olulisel määral ja ei saadud ka kinnitust oskuste omavahelisele seosele. Nii täiendati õpikeskkonda regulatiivsete uurimuslike oskuste arendamisele suunatud toetuselementidega ja viidi läbi teine alauuring. Edasiarendatud õpikeskkonnas näidati ka õpilaste regulatiivsete uurimuslike oskuste arengut ja seega oli võimalik keskenduda erinevate protsesside vaheliste korrelatiivsete seoste leidmisele. Nii näidati teise alauuringu andmete analüüsil, et kõik regulatiivsed uurimuslikud oskused olid statistiliselt olulises positiivses korrelatsioonis transformatiivsete oskustega. Samas ei olnud regulatiivsete uurimuslike oskuste tase kuigi kõrge ja nii leiti olevat oluline defineerida protsessid, mis mõjutavad uurimusliku õppe protsessi kui tervikut. Seda tehti doktoritöö kolmandas etapis.

Töö kolmandas etapis arendati esialgset uurimusliku õppe protsesside raamistikku edasi, integreerides sellega uurimuslikud metaprotsessid ja seonduvad uurimusliku õppe üldteadmised. Kirjanduse põhjal võis väita, et uurimuslik õpe peaks algama uurimuslike üldteadmiste aktiveerimisest, mis omakorda on aluseks uurimuslikele metaprotsessidele, mis seejärel juhivad tranformatiivseid ja regulatiivseid uurimuslikke protsesse. Empiiriliselt oli käesolevas töös võimalik testida korrelatiivset seost uurimuslike üldteadmiste ja transformatiivsete uurimuslike oskuste vahel. Leiti statistiliselt olulised keskmise tugevusega positiivsed seosed. Lisaks sellele raamistiku empiirilisel testimisel olulisele tulemusele leiti kolmandas alauuringus, et uurimusliku õppe protsesside täiendatud raamistiku alusel edasi arendatud õpikeskkond "Noor teadlane" võimaldab ka arendada õpilaste uurimuslikke üldteadmisi.

Kokkuvõttes viidi doktoritöös välja arendatud raamistiku testimiseks läbi kolm alauuringut. Selleks korraldati aastatel 2008 kuni 2011 neli üle-eestilist võistlust „Noor teadlane". Võistlustel osalesid õpilased 6.–12. klassini. Võistluse käigus lahendasid õpilased uurimuslikke ülesandeid veebipõhises õpikeskkonnas „Noor teadlane" (http://bio.edu.ee/teadlane/). Need ülesanded võimaldasid hinnata õpilaste transformatiivseid uurimuslikke oskusi. Lisaks paluti neil vastata küsimustele, millega oli võimalik hinnata nende regulatiivseid uurimuslikke oskusi. Õpikeskkonnas „Noor teadlane" esitati kokku viis ülesannet, milles tõstatati järgmised probleemid, millele õpilased ülesande lahendamise käigus vastuseid otsisid: miks ei õnnestu püüda kukkuvat keha, miks muutuvad meie pulss ja hingamissagedus, miks lihased väsivad erinevalt, miks kogunevad liigsed kilogrammid ning miks organism eritab vett. Õpikeskkonnast ja selle tulemuslikkusest on avaldatud ka rida loodusainete õpetajatele suunatud artikleid (nt Mäeots ja Pedaste, 2009). Kogu õppimisprotsess toimub virtuaalses klassiruumis, kus õpilasi abistab virtuaalne õpetaja ja õppijad võivad end samastada virtuaalsete õpilastega. Lisaks on õpikeskkonda sisse ehitatud rida toetuselemente, mis aitavad õpilastel näiteks sõnastada korrektset hüpoteesi. Ülesanded on üles ehitatud lähtuvalt uurimusliku õppe etappidest: probleemi sõnastamine, uurimisküsimuse sõnastamine, hüpoteesi sõnastamine, katse planeerimine, katse läbiviimine, kogutud andmete analüüsimine ja järelduste sõnastamine. Viiest ülesandest kolm vajavad reaalse eksperimendi läbiviimist ning kahe ülesande puhul kogutakse andmed, kasutades virtuaalset mudelit.

Uuringu tulemustest selgus, et alauuringud 1, 2 ja 3 võimaldasid vastata kõikidele üldistele käesolevas töös püstitatud uurimisküsimustele:

- uurimusliku õppe protsesside esialgse raamistiku põhjal arendatud õpikeskkond "Noor teadlane" oli sobiv õpilaste transformatiivsete ja regulatiivsete uurimuslike oskuste arendamiseks;
- ilmnes, et erinevad regulatiivsed uurimuslikud oskused – planeerimine, jälgimine, hindamine – korreleerusid omavahel tugevalt. Samas olid

omavahel keskmise tugevusega, kuid siiski statistiliselt olulises positiivses korrelatsioonis ka erinevad regulatiivsed oskused ja transformatiivsed oskused;
- uurimusliku õppe protsesside edasiarendatud raamistiku alusel arendatud õpikeskkond “Noor teadlane” oli rakendatav ka õpilaste uurimuslike üldteadmiste arendamiseks.

Kokkuvõttes toetasid seega erinevad empiirilised alauuringud töös koostatud teoreetilist uurimusliku õppe raamistikku. Saadud tulemused on rakendatavad õpetajate poolt, kes saavad kaaluda raamistiku sobivust uurimusliku õppe kavandamisel ka klassiruumis ja mitte ainult veebipõhistes õpikeskkondades. Eriti oluline on seejuures mõista, et uurimuslikud üldteadmised on vajalikud transformatiivsete uurimuslike protsesside aktiveerimiseks. Kokkuvõttes aitab koostatud uurimusliku õppe raamistik paremini mõista, kuidas kolm uurimusliku õppe protsessi omavahel seostuvad ning võimaldab seeläbi uute uurimuslike õppematerjalide koostamisel seda arvestada.

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ORIGINAL PUBLICATIONS

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Teadustegevus:

Minu peamiseks uurimisvaldkonnaks on uurimuslik õpe ja selle rakendamine arvutipõhistes õpikeskkondades. Täpsemalt keskendun oma teadustöös transformatiivsete ja regulatiivsete uurimuslike oskuste ja nendele suunatud toetussüsteemide uurimisele ning arendamisele**.** Olen osaline mitmes rahvusvahelises uurimusliku õppe projektis (nt Go-Lab ja Uuringulaegas).

Publikatsioonide loetelu:

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DISSERTATIONES PEDAGOGICAE SCIENTIARUM UNIVERSITATIS TARTUENSIS

1. **Miia Rannikmäe.** Operationalisation of Scientific and Technological Literacy in the Teaching of Science. Tartu, 2001.
2. **Margus Pedaste.** Problem solving in web-based learning environment. Tartu, 2006.
3. **Klaara Kask.** A study of science teacher development towards open inquiry teaching through an intervention programme. Tartu, 2009.
4. **Anne Laius.** A longitudinal study of science teacher change and its impact on student change in scientific creativity and socio-scientific reasoning skills. Tartu, 2011.
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