Turun yliopisto
University of Turku

UNDERSTANDING BIOLOGICAL CONCEPTS AT UNIVERSITY –

Investigating learning in medical and teacher education

Ilona Södervik

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
Sarja - ser. B osa - tom. 421 | Humaniora | Turku 2016

University of Turku

Faculty of Education

Department of Teacher Education

Supervised by

Professor Mirjamaija Mikkilä-Erdmann
Department of Teacher Education
Centre for Learning Research
University of Turku, Finland

Professor Erno Lehtinen
Department of Teacher Education
Centre for Learning Research
University of Turku, Finland

Reviewed by

Professor Ute Harms
Leibniz Institute for Science and
Mathematics Education
University of Kiel, Germany

Professor Anna Uitto
Department of Teacher Education
University of Helsinki, Finland

Opponent

Adjunct professor, Dr. Ilkka Ratinen
Department of Teacher Education
University of Jyväskylä, Finland

Cover photo: Ilona Södervik

The originality of this thesis has been checked in accordance with the University of Turku quality assurance system using the Turnitin OriginalityCheck service.

ISBN 978-951-29-6559-5 (PRINT)
ISBN 978-951-29-6560-1 (PDF)
ISSN 0082-6987 (PRINT)
ISSN 2343-3191 (ONLINE)
Painosalama Oy – Turku, Finland 2016

UNIVERSITY OF TURKU

The Department of Teacher Education

SÖDERVIK, ILONA: Understanding biological concepts at university – Investigating learning in medical and teacher education
Doctoral thesis, 135 p.
Education
September 2016

ABSTRACT

The aim of this dissertation was to contribute to domain-specific science learning at the university based on the research traditions of conceptual change and science learning and teaching. Previous research has shown that students have prior conceptions about scientific phenomena that often conflict with the scientific explanation and that may thus hinder or even prevent the learning of complex concepts and processes in the educational/school context. However, previous research has mainly focused on studying the conceptions of younger students. This thesis focused on the university level, and the aim was to explore teacher education students' conceptions of photosynthesis and medical students' conceptions of the central cardiovascular system. Teacher and medical education students were chosen for examination because in both study programs, learning certain biological phenomena is essential. Additionally, text-based learning plays a significant role in both study programs. In this study, the development of students' conceptions related to photosynthesis and the central cardiovascular system were studied. In addition, the roles of different texts in learning and medical diagnosing processes were investigated. The approach was both longitudinal and cross-sectional, extending the view from the group level to the single case level, including the recording of eye movements. The results showed that university students have several alarming misconceptions relating to particular scientific topics. Moreover, among medical students, the level of biomedical understanding seemed to be related to the level of clinical reasoning. However, a high-level text that specifically pointed out typical misconceptions, known as a refutational text, seemed to support learning more effectively than did a traditional text. In addition, the eye movements of internal medicine residents while reading a patient case revealed that a so-called illness script pattern seemed to be distinguishable, which highlights the importance of teaching diagnosis processes by modelling the processes of experts. To conclude, the need to develop science teaching and learning, which suggests both educational and domain-specific understanding, is evident at the university level. New teaching and learning practices, together with innovative materials, are proposed based on the results of this dissertation.

Descriptors: Conceptual change; prior knowledge; misconception; refutational text; teacher education; medical education; biomedical knowledge; clinical knowledge; eye tracking; systemic understanding; photosynthesis; cardiovascular system; science learning

TURUN YLIOPISTO

Opettajankoulutuslaitos, Turku

SÖDERVIK, ILONA: Biologian käsitteiden oppiminen yliopistossa luokanopettajan ja lääkärin ammattiin valmistavissa koulutusohjelmissa
Väitöskirja, 135 s.
Kasvatustiede
Syyskuu 2016

TIIVISTELMÄ

Väitöstutkimus kohdistuu vaativien biologian sisältöjen ymmärtämiseen yliopistotasolla. Näkökulmana ovat erityisesti käsitteellisen muutoksen sekä tiedeoppimisen ja opetuksen tutkimustraditiot. Aikaisemmat tutkimukset ovat osoittaneet, että oppilailla on runsaasti aikaisempiin kokemuksiinsa perustuvia ennakkokäsityksiä opiskeltavista luonnontieteiden sisällöistä, ja usein nämä käsitykset ovat ristiriidassa tieteellisen selityksen kanssa saattaen hankaloittaa tai jopa estää tieteellisen mallin oppimisen. Aikaisempi tutkimus on kuitenkin voimakkaasti keskittynyt peruskouluikäisten oppilaiden käsitysten tutkimiseen. Nyt tutkimuksen kohteena olivat yliopisto-opiskelijat, tarkemmin luokanopettajaopiskelijat sekä lääketieteen opiskelijat. Nämä koulutusohjelmat valittiin tukittaviksi, sillä molemmissa tiettyjen biologian sisältöjen ymmärtäminen sekä erilaisten tekstien hyödyntäminen ovat olennaisia taitoja. Tutkimuksessa selvitettiin luokanopettajaopiskelijoiden käsityksiä fotosynteesin ja lääketieteen opiskelijoiden käsityksiä verenkiertoelimistön sisältöalueista. Lisäksi tarkasteltiin erilaisten tekstien roolia oppimisen tukena ja potilasdiagnosointien tekemisessä. Tutkimuksessa hyödynnettiin kolmivuotista pitkittäistutkimusta sekä poikkileikkausasetelmia syventäen näkökulmaa ryhmätasolta aina yksittäisen oppijan prosessoinnin tarkasteluun silmänliikkeiden avulla. Tutkimuksen tulokset osoittivat, että yliopisto-opiskelijoilla on huolestuttavan runsaasti virhekäsityksiä kyseisistä biologian keskeisistä sisältöalueista. Lääketieteen kontekstissa biomedikaalinen ymmärrys oli yhteydessä kliinisen päättelyn tasoon. Tulokset kuitenkin myös osoittivat, että korkeatasoinen niin kutsuttu törmäyttävä teksti, joka tukee virhekäsitysten muokkaamista kohti tieteellistä ymmärrystä, voi edistää oppimista tehokkaammin kuin perinteinen, selittävä teksti. Edelleen erikoistuvien lääkäreiden lukuprosesseissa oli nähtävissä aikaisempien potilastapausten aktivointi silmänliikkeissä. Tämä mahdollistaa asiantuntijoiden silmänliikkeiden käytön diagnosointiprosessin mallittamisessa opetuksessa. Näin ollen tämän väitöstutkimuksen osatutkimusten tulosten pohjalta nousee tarve kehittää biologian oppimista ja opetusta yliopistotasolla, mikä edellyttää sekä kasvatustieteen että ainespesifien sisältöjen tutkimusperusteista ymmärtämistä. Tulosten avulla ehdotetaankin uusia opetuksen ja oppimisen käytäntöjä sekä ideoita uusien innovatiivisten oppimateriaalien kehittämiseksi.

Asiasanat: Käsitteellinen muutos; aikaisempi tieto; virhekäsitys; törmäyttävä teksti; luokanopettajakoulutus; lääketieteen koulutus; biomedikaalinen tieto; kliininen tieto; silmänliiketutkimus; systeeminen ymmärrys; fotosynteesi; verenkiertoelimistö; tiedeoppiminen

ACKNOWLEDGEMENTS

There is only one name on the cover page, but it is obvious that this thesis is the result of teamwork. Although I have enjoyed this project, like all truly significant things in life, it has sometimes been challenging. I am therefore indebted to several people for their support and help in both academic and non-academic matters during this long journey.

I would like to express my sincerest gratitude to my supervisors, Professor Mirjamaija Mikkilä-Erdmann and Professor Erno Lehtinen, who have facilitated my scientific thinking by offering an exceptionally inspiring work community and constructive feedback when needed. It has been a huge privilege to follow in a strong research tradition under the supervision of two top experts.

First and foremost, I want to thank Mirjamaija for her strong belief in me and for the countless learning opportunities she has offered me. She has an ability to guide students in a gentle and supportive manner, and many times she has believed in me much more than I myself have done, which has pushed me to learn more and more. She is also a true role model of a strong woman who is able to combine work and family. The countless academic discussions we have had in her office over the years have been the best lessons during this journey. For all this, and much more, I am forever grateful.

I would also like to warmly thank Professor Erno Lehtinen for his supervision. I truly admire his intelligence, kindness and deep scientific understanding. Discussions with him have always encouraged and inspired me and have definitely helped improve my work.

I would like to thank Adjunct Professor Ilkka Ratinen from the University of Jyväskylä for accepting the invitation to act as the opponent in my effort to defend this thesis. Furthermore, I was privileged to have very competent reviewers for my thesis in Professor Ute Harms from the Leibniz Institute for Science and Mathematics Education, University of Kiel and Professor Anna Uitto from the Department of Teacher Education, University of Helsinki. I want to thank them for their excellent insights and productive comments concerning this thesis.

Additionally, I would like to thank Professor Emeritus Erkki Olkinuora for his collaboration and insightful comments related to my several manuscripts and this thesis. I also want to thank Professor Emeritus Pekka Kääpä and Professor Juhani Airaksinen from the Faculty of Medicine who provided their medical expertise for our studies with a medical context.

I would also like to express my deepest thanks to my colleagues. Many thanks go to my closest colleague and even closer friend Dr Henna Vilppu, with whom I have shared the same office, most of the data collection phases related to this thesis and countless lunch-time discussions. Thank you for your collaboration, support and friendship. I also want to thank Dr Viivi Virtanen from University of Helsinki, MA Katri Kotamäki, MA Erkki Anto and Dr Marjaana Puurtinen from the Department of Teacher Education, Turku, MA Erika Österholm, TUTKE and teaching nurses Tiia Bergman and Helena Haapanen from the Faculty of Medicine, Turku for their cooperation.

I would like to thank the numerous participants in all five sub-studies for their time and contributions. Further, this work would not have been possible without generous financial aid from various sponsors. I want to thank the following funding agencies: the Finnish Cultural Foundation and its Varsinais-Suomi Regional Fund for two personal grants, the Academy of Finland via the LeMed and LearnMedImage projects and the Doctoral Programme on Learning, Teaching and Learning Environments Research (OPPI).

I also wish to extend a few words of thanks to some of the people in my personal life. I have been lucky enough to meet many of my closest friends at school. It is good to know that I have true friends with whom I can be my real self and who I can always count on. So, thank you Henna, Elsi, Leena, Maria, Saana Sirpa and Tytti.

To my Mum and Dad, you have provided me and my siblings the best possible foundation for life, for which I will be forever thankful. You provided a warm and gentle home where education and open discussions were highly appreciated. Your support and belief in me has brought me to where I am now. Emilia and Joose, I am happy to have such loving and brilliant siblings who share my interest in science and from whom I can learn so much. Thank you for everything. I am also grateful to my parents-in-law, Elisa and Markku, who have supported my work by frequently taking care of Noel and Elea.

Last, I want to thank my very immediate family. Juha, you are my bedrock and my home is beside you. It is easy to chase even the wildest dreams with the support of such a stable and calm soulmate. I want to thank you for your mental and practical support during this journey. Noel and Elea, you mean the world to me. Being your mother has taught me more about life than anything else. I love you more than I will ever be able to express. Hopefully, I will be able to support you in chasing your dreams, whatever they may be.

Turku, August 8, 2016

LIST OF ORIGINAL PUBLICATIONS

Study I Ahopelto, I., Mikkilä-Erdmann, M., Anto, E., Penttinen M. (2011). Future Elementary School Teachers' Conceptual Change Concerning Photosynthesis. *Scandinavian Journal of Educational Research*, 55 (5), 503–515.

IA contributed to the design of the study material, and was responsible for the analysis and the interpretation of the data and writing the manuscript. MM-E, EA and MP were responsible for designing the study and the study material. MM-E contributed writing the manuscript. EA and MP were responsible for collecting the data. All authors critically revised the manuscript and approved the final version for publication.

Study II Södervik, I., Mikkilä-Erdmann, M., Vilppu, H. (2014). Promoting the Understanding of Photosynthesis among Elementary School Student Teachers through Text Design. *Journal of Science Teacher Education,* 25, 581–600.

IS contributed to the study conception and design; designing the study material; was responsible for the data collection, analysis and interpretation and writing the manuscript. MM-E contributed to the study conception and design; designing the study material and wrote the manuscript. HV contributed to the study design and helped with data collection. All authors critically revised the manuscript and approved the final version for publication.

Study III Mikkilä-Erdmann, M., Södervik, I., Vilppu, H., Kääpä P., Olkinuora, E. (2012). First-year Medical Students' Conceptual Understanding of and Resistance to Conceptual Change Concerning the Central Cardiovascular System. *Instructional Science*, 40, 745–754.

MM-E contributed to the study conception and design and was responsible for writing the manuscript. IS contributed to the study design and designing the study material; was responsible for the data collection, analysis and interpretation and writing the manuscript. HV contributed to the study design; data collection, analysis and interpretation and writing the manuscript. PK contributed to the study design and commented on the study material as a content specialist. EO contributed to the study conception and design. All authors critically revised the manuscript and approved the final version for publication.

Study IV Ahopelto, I., Mikkilä-Erdmann, M., Olkinuora, E., Kääpä, P. (2011). A Follow-up Study of Medical Students' Biomedical Understanding and Clinical Reasoning Concerning the Cardiovascular System. *Advances in Health Sciences Education,* 16, 655–668.

IA contributed to the study conception and design; was responsible for the data collection, analysis and interpretation and for writing the manuscript. MM-E contributed to the study concept and design and interpretation of the data. EO contributed to the study conception and design. PK contributed to the study conception and design and commented on the study material as a content specialist. All authors critically revised the manuscript and approved the final version for publication.

Study V Södervik, I., Vilppu, H., Österholm, E., Mikkilä-Erdmann, M. (*in review*). The Relationship between Biomedical and Clinical Understanding in Medical Students and Residents – Combining Eye-tracking and a 3-year Follow-up

IS contributed to the study conception and design; was responsible for developing the patient case texts; contributed to the data collection, analysis and interpretation and was responsible for writing the manuscript. HV contributed to the study conception and design and data collection. EÖ contributed to the data collection and analysis. MM-E contributed to the study concept and design and interpretation of the data. All authors critically revised the manuscript and approved the final version for publication.

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Intentional conceptual change as a goal of science learning

This dissertation takes a domain-specific approach to learning complex biological phenomena in higher education. Inspiration for the thesis is drawn from both current learning research—particularly that related to conceptual change—and from the research tradition of science learning and teaching. The principal ideas of these traditions relating to this research are discussed in this introduction.

The research tradition of conceptual change became a focus of learning in the 1970s and has lately become one of the leading paradigms in the research on science teaching and learning (Posner, Strike, Hewson & Gertzog, 1982; Treagust & Duit, 2008). The concept of conceptual change was first introduced by Thomas Kuhn (1962) to indicate that the meanings of concepts embedded in a scientific theory change when the theory changes (Vosniadou, 2013). The term 'conceptual change' refers to the idea that learning is not only about acquiring new information and piling fact upon fact but about recognizing that existing knowledge structures often have to fundamentally change (diSessa, 1993).

Previously, based on empiricist conceptions of learning, students were thought to come into learning situations with a blank mind, a tabula rasa, meaning that previous knowledge of themes to be studied was not seen as a relevant factor affecting the learning of new knowledge. However, over the past decades, research has conclusively shown that students actually come to science lessons loaded with expectations, previous knowledge and prior conceptions that in some cases significantly contradict the scientific view (Carey, 1985; Chinn & Brewer, 1993; Duit & Treagust, 2003; Vosniadou, 1994; 2013; Limón, 2001; Broughton, Sinatra & Nussbaum, 2013; Diakidoy, Kendeou & Ioannides, 2003; Mason, 2001; Mikkilä-Erdmann, 2002; Vosniadou & Skopeliti, 2005). This means that students' prior conceptions relating to a topic to be learned may not always facilitate learning but rather can lead to systematic misinterpretations. Therefore, to reach a scientific understanding often means reorganising one's existing knowledge structures and sometimes even abandoning certain existing conceptions—a process that usually happens gradually and suggests intentional learning and teaching (e.g. Chi & Roscoe, 2002; Sinatra & Pintrich, 2003). This kind of learning is described using the theories of conceptual change (see Posner et al., 1982; Vosniadou, 1994; Chi, 1992; Limón & Mason, 2002).

In the conceptual change research tradition, two types of learning can be differentiated: *enrichment*, a weak conceptual change that is also conceptualised as assimilation by Jean

Piaget (1970), and *revision*, a radical conceptual change or accommodation, as Piaget (1970) called it (see Vosniadou, 1994). In enrichment, one only adds new information to existing knowledge structures if the new information does not conflict with the learner's existing concepts. For example, one may know that plants are capable of photosynthesis and then may have learned more precisely that photosynthesis occurs in the green parts of plants because leaf and stem cells contain cell organs called chloroplasts, containing green chlorophyll pigment, where photosynthesis takes place. That would be assimilation, as the new information does not conflict with the existing knowledge but adds to it. Revision is required if new information and existing knowledge conflict. For example, in the previous example, one learned that photosynthesis happens in the green parts of a plant, as the process takes place in chloroplasts containing green chlorophyll pigment. If the same person now hears that actually there are also certain non-green coloured organisms—such as certain algae and even bacteria—that are capable of photosynthesis, prior knowledge will need to be adjusted. In accommodation, it is not just simply about replacing old conceptions with new ones, but some kind of knowledge restructuring also has to occur (see Posner et al., 1982).

As students often enter the science classroom with prior conceptions that may hinder understanding of the scientific model, a common approach to fostering conceptual change has based on a so-called cognitive conflict strategy (see Chan, Burtis & Bereiter, 1997). This means that to get students to change their initial ideas, their typical misconceptions must be placed in contrast with the scientific model to induce a cognitive conflict (see e.g. Chan et al., 1997; Limón, 2001). Cognitive conflict can be defined as mental discomfort that manifests when the coherence of one's knowledge structures is threatened. However, cognitive conflict as such does not automatically result in a conceptual change. Learning researchers have published a number of studies in which the idea has been to arrange interventions aimed at inducing a cognitive conflict to foster conceptual change, but the results have not been supportive (see Limón, 2001). This is because the problem in practice is often that, although confronted with contradictory information, students may not experience a real need to change their prior understanding. Because a cognitive conflict is usually an unpleasant experience, instead of modifying previous misconceptions, people often staunchly maintain the old ideas and reject or distort new ones (Chinn & Brewer, 1993). Moreover, students may construct a so-called synthetic model that has characteristics of both scientific and naïve explanations (see Vosniadou & Brewer, 1992). Synthetic models develop if one adds new information to old knowledge structures and ignores the conflicts between them (Vosniadou & Brewer, 1992). Research has shown that synthetic models are often relatively coherent and provide a seemingly explanatory power for the learner and therefore are rather difficult to revise (Vosnadou, 1994; see also Sinatra & Mason, 2013). In synthetic models concerning photosynthesis, one may know, for example, that according to the scientific model green plants are able to produce nourishment in the process of photosynthesis but still think that in the spring a farmer spreads nutrients onto the field so that plants get 'food' to grow (see e.g. Mintzes & Wandersee, 2005; Roth, 1990).

Therefore, unless the learner's *metaconceptual awareness* starts to guide the learning process, s/he will be unable to solve the cognitive conflict successfully (see Limón, 2001; Vosniadou & Ioannides, 1998). Metaconceptual awareness means that one becomes aware of the discrepancies between his/her previous conceptions and the scientific explanation and is able to weigh them critically. Metaconceptual awareness is usually a prerequisite for conceptual change because it induces dissatisfaction with one's previous inaccurate conceptions (see Posner et al., 1982; Vosniadou, Ioannides, Dimitrakopoulou & Papademetriou, 2001; Broughton et al., 2013; Lombardi, Sinatra & Nussbaum, 2013). Besides *dissatisfaction*, Posner et al. (1982) state that certain other conditions also need to be fulfilled to enable conceptual change. Conceptual change suggests new information be *intelligible*, meaning sufficiently clear; *plausible*, meaning reasonably true and *fruitful*, meaning potentially productive (Posner et al, 1982). In other words, students must be convinced that the new concept offers them more explanatory power than their existing concept affords (Hynd & Guzzetti, 1998). This explains why conceptual change is nearly impossible to achieve without intentional and systematic studying and teaching (Chinn & Brewer, 1993).

To conclude, research on conceptual change has become one of the most important areas in science learning and instruction since the 1970s. There are various perspectives and traditions in the conceptual change research field (see e.g. Duit, Treagust & Widodo, 2013; Vosniadou, 2013), the most important of which from the point of view of this dissertation have been presented in this chapter.

1.2 Conceptual learning in science – different roles of prior knowledge

Research concerning the role of students' pre-instructional conceptions in learning has indicated that the quality of previous knowledge plays a critical role in learning (see Bransford, Brown & Cocking, 2000). Previous knowledge that is a necessary prerequisite for all conceptual learning may hinder learning if there are discrepancies between the old 'knowledge' and new information, for example, when the new information does not fit into one's knowledge structures as such but suggests the necessity of reorganising or even rejecting some previous conceptions (for a review, see diSessa, 2006). This paradox of learning poses a challenge for science instruction (Sinatra & Mason, 2013).

Human beings are flexible learners and from infancy are active agents in acquiring knowledge that helps them to understand, foretell and interpret their surroundings (see e.g. Donovan & Bransford, 2005; Denis, Williams, Dunnamah & Tumba, 2015). According to *framework theory* (Vosniadou, 2013), young children already develop knowledge structures of, for example, naïve biology (Inagaki & Hatano, 2013) and naïve physics (Vosniadou 2013; for an opposing view of naïve ideas as phenomenological primitives or p-prims rather than theory-like representations, see e.g. diSessa, 2006). Naïve physics, for example, does not consist of fragmented observations but forms a relatively coherent explanatory system concerning basic astronomical and physical phenomena.

However, reaching conceptual change and thus scientific understanding of certain scientific phenomena often requires crucial reorganisation—such as ontological and epistemological changes—of these framework theories (see Treagust & Duit, 2008; Chi & Slotta, 1993; Vosniadou, 2013). Chinn and Brewer (1993) discuss the fundamental categories and properties of the world that describe ontological beliefs. Typical examples are the concepts of heat, energy, genes and photosynthesis, the understanding of which often requires an ontological shift from the category of 'matter' to the category of 'process' (Aivelo & Uitto, 2015; Barak, Sheva & Gorodetsky, 1999; Chi, 2008; Duit et al., 2013; Wiser & Amin, 2001). However, because these naïve beliefs have typically developed over a long period of time and are used to support ideas across many domains or sub-domains, they are very robust and hard to change without consistent, intentional and often long-term instruction (see Chi, 1992; Sinatra & Mason, 2013).

Prior conceptions that one has adopted through informal learning in everyday situations and that are not consistent with current scientific understanding may be called alternative conceptions, alternative beliefs, naïve conceptions, prior conceptions, misinformation or misconceptions, depending on the perspective and underlying assumptions about cognition and learning (see e.g. Driver, 1989; Scott, Dyson & Gater, 1987; Hewson, 1982). For consistency and because of long-standing tradition, the term misconception is used throughout this thesis, although the concept and its definition are somewhat problematic (for a critical examination of the concept, see chapter 5.2). By the concept of misconception, we mean a conception that differs from current scientific understanding.

Recognising the origins and characteristics of misconceptions is essential when trying to understand why the learning of certain scientific concepts poses challenges for students and how learning can be supported. First, *physically derived* misconceptions, which have their origins in interactions with the physical environment (Guzzetti, Snyder, Glass & Gamas, 1993), can be distinguished. They may typically be falsely confirmed by perceptions that offer only limited explanations. For example, a young child sees the sun 'rising' in the morning and 'setting' at night but later learns at school about Copernicus' idea that the sun does not actually move anywhere and that rather it is the rotating Earth that causes this perception. These kinds of misconceptions typically develop in childhood; they get confirmed by everyday notions and therefore seem to work well enough in everyday life. Although not consistent with current scientific knowledge, such misconceptions are often robust and have a lot of explanatory power in everyday life. Therefore, they are very hard to revise in formal education (see Vosniadou, Vamvakoussi & Skopeliti, 2008).

Misconceptions can also be *instructionally derived*, having their origins in previous formal educational experiences (Guzzetti et al., 1993). For example, they may well derive from learning materials that only have limited possibilities to present interactions between concepts or the simultaneous nature of some processes. In addition, learning is a social activity that takes place in a complex sociocultural world (see Vosniadou, 2008), and social interactions, language and cultural conventions affect our thinking and learning, both consciously and unconsciously. Misconceptions that have their origin in social interactions may be called *socially derived* misconceptions (Guzzetti et al., 1993). These misconceptions may be due, for example, to the problem of two conceptualisations (see Wiser & Amin, 2001). This means that one concept may have different interpretations in scientific discussions compared to everyday contexts. According to Vygotsky (1994), there are two main types of concepts, spontaneous and scientific. He emphasises that scientific concepts cannot be learned without systematic support from a more knowledgeable person, such as a teacher. For example, some scientific concepts, such as *force* and *heat*, are part of both science language and everyday language, and a learned person is able to actively use appropriate concepts depending on the context. However, for students who are not aware of these differences, this poses a challenge. Therefore, certain concepts that children use are incommensurable with concepts that more experienced people, such as teachers, use. For example, the concept of heat is often misunderstood by students because they relate heat to hotness, whereas the scientific view of heat is of exchanged energy (see Wiser & Amin, 2001). It is important to note here that despite this classification of the origins of misconceptions, in real life misconceptions with different origins mix and combine. For example, a misconception related to the sunrise or sunset that a child typically adopts by observing his/her physical environment is constantly confirmed in everyday social interactions and discussions and sometimes even in instructional experiences, where it is learned, for example, that the sun rises in the east and sets in the west.

Misconceptions exist in almost every subject area, but they seem to be especially prevalent in science (Maria, 2000). Over the last few decades, researchers have published many studies identifying misconceptions in different scientific domains. Students of varying age have been found to have difficulty understanding a number of scientific concepts, such as photosynthesis (Brown & Schwartz, 2009; Duit & Treagust, 2003; Mintzes & Wandersee, 2005; Roth, 1990), cellular respiration (Brown & Schwartz, 2009), Newton's laws of motion (Kendeou & van den Broek, 2007), tides (Ariasi & Mason, 2011), seasonal change (Broughton, Sinatra & Reynolds, 2010), the cardiovascular system (Chi, 2005; Windschitl & Andre, 1998) and energy (Diakidoy, Mouskounti & Ioannides, 2011). Identifying misconceptions is a major part of the conceptual change research tradition because it has helped us to understand the challenges relating to the learning of complex scientific domains and to realise that misconceptions often hinder reaching a deeper systemic understanding of scientific phenomena.

1.3 Systemic understanding suggests a domain-specific approach

The complex and multifaceted nature of most scientific concepts requires a systemic understanding, that is, an understanding of how separate concepts and facts combine to form a complex network (see Barak, Sheva & Gorodetsky, 1999; Mayr, 1997; Verhoeff, Waarlo & Boersma, 2008). Systemic understanding suggests that one can 'run' a mental model to predict future states of a system or to explain the cause of a change in the state of a system (Kaufman, Keselman, Patel, 2008; for mental models, see Johnson-Laird, 1983). Although the learning of facts is also important, knowing a system's components alone does not ensure students' understanding of interrelationships and entities (Eilam, 2012; Wadouh, Liu, Sandmann & Neuhaus, 2014). This means that in addition to understanding several single concepts, one also has to know the relationships between different facts and how they interact with their surroundings. Systemic understanding would enable the flexible use of concepts as effective tools instead of static and isolated 'islands' of knowledge (see also Uitto, 2012).

The importance of systemic understanding in learning science has become unquestioned among science education researchers over the past decade (see Branstädter, Harms & Groβschedl, 2012). For the biology discipline, this means that understanding causal explanations between, for example, structures and processes by asking questions starting with *what kind of*, *how* and *why*, is essential. For example, 'What kind of structure does a human heart have?' 'How does the structure function?' 'Why is the structure how it is?' However, science instruction in the school curriculum has been criticised, for example, because biological processes are often reduced to separate facts instead of being looked at as systemic wholes (Barak et al., 1999; Plate, 2010). Therefore, there is a high risk that science learning remains as fragmented and unrelated facts, which presumably prevents the transfer of knowledge and using concepts as effective and intellectual tools in various situations.

In investigating systemic understanding and the need for conceptual change related to science concepts, a domain-specific perspective is inevitable and crucial. This is because the kinds of changes necessary are often fundamentally different for different domains and even sub-domains (Treagust & Duit, 2008). Therefore, in order to, for example, understand how to frame and ask meaningful questions about a certain topic, at least a good understanding of the subject area is needed. However, in the research tradition of conceptual change, the domain-specific perspective has often taken a back seat, meaning that there has been little focus on reflecting about which special characteristics make the learning of certain concepts difficult, which kinds of misconceptions are typical, what the significance of understanding certain concept for students is, etc. As Duit (2009) comments, in many studies about conceptual change the major emphasis has been on implementing new instructional methods and not on rethinking the presentation of the particular science topic.

In this dissertation, two complex, multifaceted biological concepts are examined—photosynthesis and the central cardiovascular system (CCVS) of the human body. There are a number of pedagogical reasons these topics are suitable for studying conceptual change at the university level. First, common to the concepts of photosynthesis and the CCVS is that they can be called key concepts in biology. This is because knowing about them is crucial when trying to understand several other important biological phenomena (regarding key concepts, see e.g. Chambliss & Calfee, 1998). In addition, comprehending these concepts requires a systemic understanding in which several concepts are involved in an intricately, causally connected way.

Further, both concepts are partly covert and partly observable, meaning that young children have already had at least some previous experience related to these phenomena in their everyday lives. Nevertheless, observation alone does not result in a deep understanding of these phenomena but may lead to misinterpretations. Previous studies have shown that people, both children and adults, often stubbornly hold onto their misconceptions about these concepts. However, these concepts have their own unique aspects that make learning about them challenging. These are discussed in the following chapters.

1.3.1 Photosynthesis as a conceptual challenge

> ‘Life on Earth is solar powered. The chloroplasts of plants capture the light energy that has traveled 160 million kilometers from the sun and convert it to chemical energy stored in sugar and other organic molecules. The conversion process is called *photosynthesis*.’
>
> (Campbell & Reece, 2002)

Photosynthesis is one of the most central and complex biological phenomena. On one hand, it has enabled life on Earth as we know it, and on the other hand it is ever present in our daily lives. Not many of us reflect on the fact that all life on Earth depends on the ability of green plants to produce oxygen and to transform solar energy into chemical energy and further that substances we consume every day, such as food, oil and wood, are produced by photosynthesising organisms. Furthermore, sufficient understanding of current critical, ecological and financial dangers, such as climate change, famine and running out of fossil fuels, necessitates understanding the basics of photosynthesis. Therefore, it can be suggested that the average human being as a decision maker should understand at least the fundamentals of the photosynthesis phenomenon.

Studying photosynthesis is greatly emphasised in school curricula in Finland, and the concept is studied several times during the comprehensive school years. Despite this, misconceptions (see Brown & Schwartz, 2009; Crane & Winterbottom, 2008; Mintzes & Wandersee, 2005; Ross, Tronson & Ritchie, 2005) and synthetic ideas (see e.g. Mintzes & Wandersee, 2005; Vosniadou, 1994; Mikkilä-Erdmann, 2001; Roth, 1990) of photosynthesis commonly exist among both children and adults, which is something that needs to be addressed.

First of all, a proper understanding of photosynthesis requires several changes of perspective. For example, young children often categorise plants as non-living things (Vosniadou et al., 2008; see also Carey, 1985). Later, children learn what distinguishes living and non-living things and through everyday experiences—such as seeing that plants can grow, that they need to be watered and that they can die—they learn to re-categorise plants as living things (Vosnadou et al., 2008). Such re-categorisation often happens before a child enters school. However, there is another challenge within the ontological category of living organisms that may result in misconceptions, even for adults.

For example, most of us know that a houseplant will die if we forget to water it. Misconceptions related to the ontological difference between animals and plants may lead us to link water for plants with food for animals. Understanding the fundamental differences between animals and plants is a prerequisite for understanding the role of photosynthesis in the ecosystem. To clarify, plants and animals should be categorised into the different ecological groups of autotrophic producers (plants) and heterotrophic consumers (animals). Plants need only the raw materials for photosynthesis—water and carbon dioxide—together with a variety of minerals from their surroundings. By using solar energy, they produce chemical energy by themselves in the photosynthesis process (see Figure 1). Animals, however, get their energy from the food they eat. Therefore, heterotrophic animals are dependent on autotrophic organisms that transform inorganic compounds into organic ones and that are producers of the ecosystem.

Additionally, learning about photosynthesis may cause challenges because of the double-edged nature of the phenomenon. As suggested earlier, photosynthesis is a process that is partly observable and therefore familiar even to small children and partly so intangible and complex that even plant physiologists do not know the entire process. The possibility of artificial photosynthesis has been investigated for a long time with no breakthroughs, which gives an idea of the complexity of the process. The deceptive illusion of simplicity, perhaps deriving from the everyday nature of the phenomenon, may wrongly persuade learners to reduce this multifaceted phenomenon to a too simple process unconnected to the ecosystem as a whole, as seen in several previous studies (see, e.g. Mintzes & Wandersee, 2005).

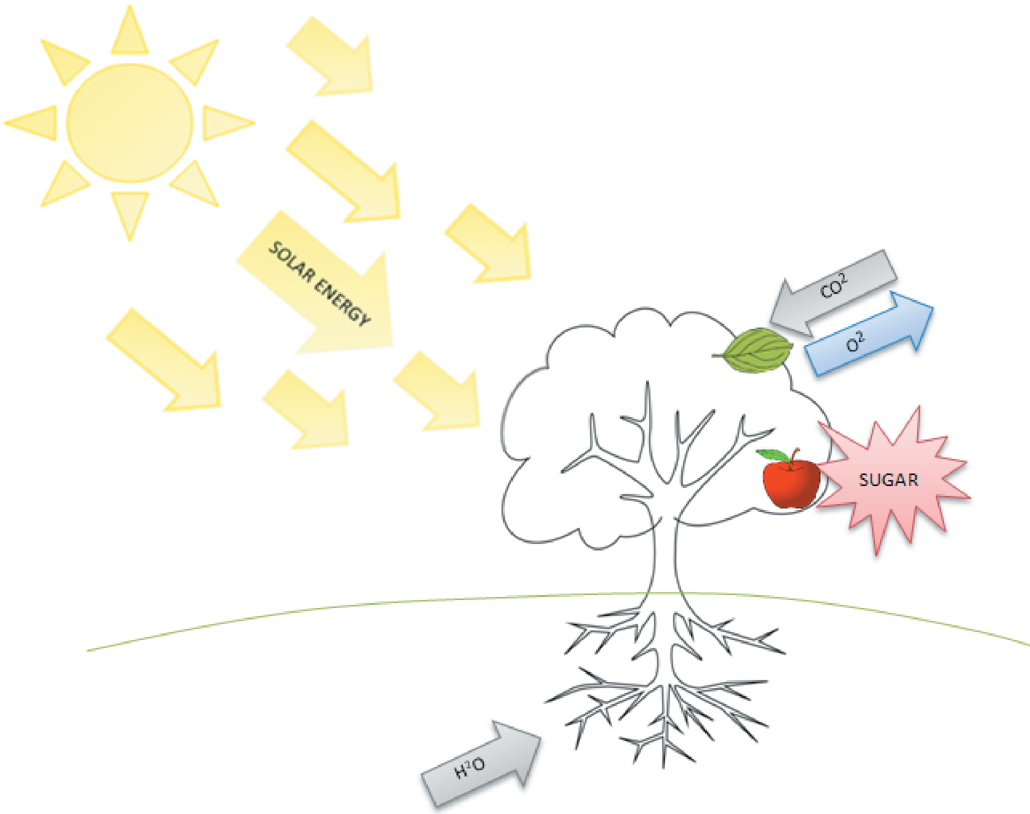

Figure 1. Basic idea of photosynthesis.

1.3.2 The central cardiovascular system as a conceptual challenge

The cardiovascular system is in charge of transporting substances in the human body. The anatomy and physiology of the human CCVS (see Figure 2) are very basic aspects of human biology that are studied several times from elementary school to high school. The CCVS is also one of the first topics covered in medical education at the university level. The cardiovascular system has such a central role in the human body that understanding the basics is crucial to comprehend how different systems in the human body work together. Understanding the CCVS requires learning a great number of individual concepts and a systemic understanding. However, previous studies have shown that medical students often study physiological topics using rote memory and are therefore unable to understand co-operative interactions between concepts, to transfer knowledge to other contexts and to solve clinical problems later on (see González, Palencia, Umaña, Galindo & Villafrade, 2008).

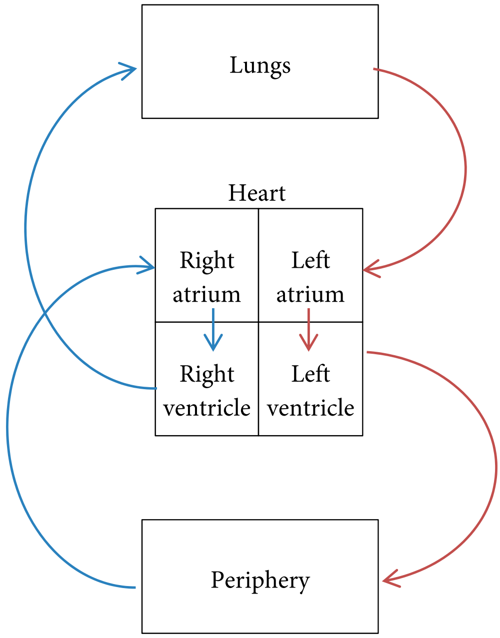

Figure 2. Basic structure of the central cardiovascular system. Red arrows indicate oxygen-rich blood, and blue arrows indicate oxygen-poor blood.

In general, the cardiovascular system transports substances, such as oxygen, nutrients, hormones, carbon dioxide and other metabolic waste products, inside the human body in which the heart acts as a tireless pump. In this study, however, the focus is on the transportation of oxygen and carbon dioxide in the CCVS.

The effectiveness of mammals' circulatory systems compared with those of, for example, reptiles or fish is due to a great extent to the anatomy of the heart. The human heart, as do the hearts of all mammals, consists of four chambers (upper right and left atria and lower right and left ventricles). The right and left sides of the heart are separated by a muscular wall—the atrioventricular septum—that prevents the mixing up of oxygen-rich and oxygen-poor blood. The right side of the heart (right atrium and ventricle) takes care of oxygen-poor blood. When the heart contracts, blood from the right ventricle is pumped through the pulmonary artery into pulmonary circulation (and at the same time, the blood from the left ventricle is pumped through the aorta into systemic circulation). In the lungs, red blood cells are loaded with oxygen molecules, and this oxygen-rich blood returns to the left side of the heart. When the heart again contracts, blood from the left ventricle goes to systemic circulation via the aorta. Within the capillaries of peripheral tissues and organs, blood gives up much of its oxygen, and carbon dioxide, produced by cellular respiration, is picked up in exchange. This oxygen-poor blood then returns from the periphery back, this time to the right side of the heart.

There are three types of blood vessels. Each is built of similar tissues but has different anatomical structures that correlate with their functions. Arteries are the vessels that bring blood from the heart to either systemic or pulmonary circulation. Therefore, arteries have thicker walls compared to veins to accommodate the high blood pressure from the heart. In veins that bring the blood from the organs to the heart, the blood pressure is much lower. In veins, there are valves that inhibit the backward flow of blood when blood pressure decreases and blood needs to be transported from the peripheries back to the heart. The third type of blood vessels is capillaries, which have only very thin walls because the exchange of the subjects takes place within them.

The above is only a brief and very general description of the human CCVS. However, researchers have found that there are certain typical misconceptions about this basic system that commonly exist among both elementary school students and university students (see, e.g. Chi, 2005, 2008; Kaufman et al., 2008; Michael et al., 2002; Wadouh et al., 2014; Windschitl & Andre, 1998). One common misconception among adult students is the idea of the heart as a single pump, which means that the circulation system is often considered as one path, and pulmonary circulation is either completely ignored or poorly understood (see, e.g. Chi, 2005; 2008; Michael et al., 2002; Windschitl & Andre, 1998). Another typical misconception involves the difficulty in understanding the simultaneous nature of the circulatory system, where the right and left ventricles of the heart contract in unison. This misconception is referred to as the 'serial loop' misconception because the interaction of the two loops or paths of the circulatory system is not correctly understood. Furthermore, for both children and adults who on one hand are familiar with the phenomenon of gravitation but do not know how the valves in the veins function, it is typically difficult to understand how blood can flow in only one direction and particularly from the legs upward to the heart (see, e.g. Chi, Chiu, & deLeeuw, 1991).

The heart is generally the first internal organ that preschool children are able to name and situate, although they typically do not have any idea about circulation yet (Carey, 1985). Actually, understanding the fact that blood returns back to the heart is reported to cause difficulties for children as old as 16 (see Carey, 1985). Further, several misconceptions related to the cardiovascular system may have their origins in previous instructional experiences, as textbooks only have a limited opportunity to support the understanding of simultaneous processes and therefore systemic understanding. In addition, discussions about the cardiovascular system and the respiratory system are presented separately in textbooks and for practical reasons are studied separately in science classrooms. This may hinder understanding of the inseparable interaction of these systems. It can be suggested that certain misconceptions about the CCVS may derive from observations of our physical environment and of our own bodies. For example, we can perceive our pulse by placing our fingers at certain points, such as on the wrist or neck, and can even hear the pumping of the heart using a stethoscope; however, we are unable to sense the gas exchange taking place in the lungs. Our perceptions of our physiological environment might therefore hinder the proper understanding of the double-loop function of the circulatory system. Overall, it can be said that conceptual change is needed to gain a thorough and deep understanding of the CCVS (Chi, 2008).

1.4 The role of the reading process in supporting science learning

Understanding of the multifaceted biological concepts of photosynthesis and the cardiovascular system requires much support in the learning environment, such as from learning material. As a great part of learning still occurs through reading, textbook texts still seem to be one of the most important tools in science learning, (Mikkilä-Erdmann, 2002; Mason, Gava & Boldrin, 2008; Tippett, 2010). However, although the role of textbooks is inevitable, traditional science textbooks have been criticised for several reasons. First, it has been stated that textbooks do not particularly take readers' prior knowledge into account. Often, they present scientific models as if readers have no prior knowledge or have only relevant prior knowledge about the topic to be learned (Chambliss, 2002; Mikkilä-Erdmann, 2002). Second, biological processes are often presented separately in textbooks, which may hinder the construction of a systemic understanding (Barak, et al., 1999). This may prevent deep understanding of biological concepts and can often lead to the reproduction of isolated facts instead of the achievement of conceptual change. Last, certain concepts are inaccurately presented in science textbooks that do not contain the most up-to-date information (see, e.g. Aivelo & Uitto, 2015).

A common idea about text comprehension is that readers construct different kinds of mental representations during reading (Mikkilä-Erdmann, Penttinen, Anto & Olkinuora, 2008). Kintsch (1988) has named two different types of representations occurring during reading: text-based representations and situational models. The former is constructed from the semantic content of the text, meaning that it consists of those elements and relationships that are directly derived from the text itself (Kintsch, 1998). The latter refers to readers' comprehension processes, in which text is integrated into the readers' previous knowledge and into the larger context (Kintsch, 1998). Thus, mental representations are constructed from the whole during reading (Kintsch, 1986). According to Kintsch's (1988, 1998) well-known model, readers' prior knowledge therefore plays an essential role in text comprehension, and inaccurate prior conceptions may act as a barrier to the construction of a situational model from the text (Sinatra & Mason, 2013). Because text features can influence learning from text, designing specific texts might play a role in supporting conceptual change (Ariasi & Mason, 2011).

As also discussed in section 1.1., conceptual change can be fostered when providing learners with opportunities to weigh the scientific evidence against their existing knowledge (Broughton et al., 2013). This necessitates the activation of readers' metaconceptual awareness, which is the main objective in using so-called *refutational texts*. Refutational text is a type of text designed to awaken readers' metaconceptual awareness by systematically pointing out typical misconceptions about certain concepts and thus helping learners revise their mental model (Hynd, 2001). A refutational text usually includes three elements: the presentation of a typical misconception about a certain topic, a refutation and the correct explanation to help learners revise their possible misconceptions (see Figure 3) (Hynd, 2001). As mentioned, giving up misconceptions in favour of current scientific views takes a lot of persuasive power and support, something that a refutational text can offer. Kendeou and van den Broek (2007) conceptualise this phenomenon as co-activation, when readers' previous misconceptions and scientific ideas are active at the same time in the working memory, which enables an effective comparison between them.

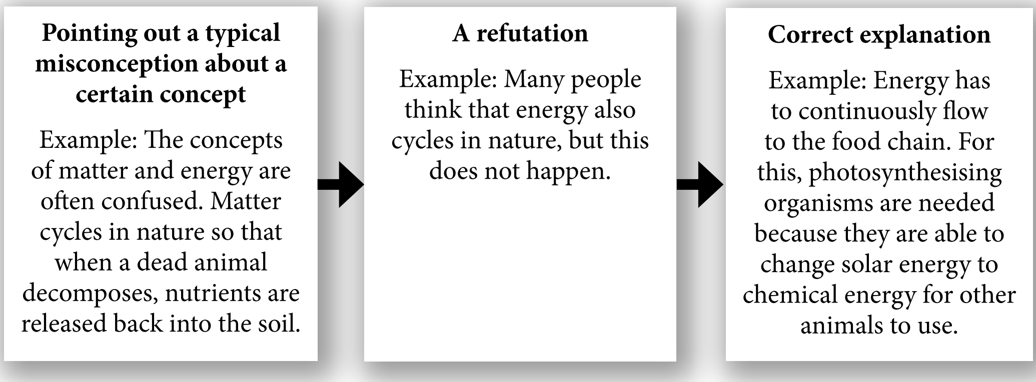

Figure 3. Typical structure of a refutation. Refuting examples from Södervik, Mikkilä-Erdmann & Vilppu, 2014.

The conceptual change potential of refutational texts has been investigated since the mid-1980s (for a review, see Tippett, 2010). Previous studies have presented a number of examples of the effectiveness of refutational texts in science learning in different domains (see, e.g. Alvermann & Hague, 1989; Ariasi & Mason, 2011; Braasch, Goldman & Wiley, 2013; Diakidoy et al., 2003; Guzzetti, Williams, Skeels & Wu, 1997; Mason et al., 2008; Mikkilä-Erdmann, 2001) compared to traditional textbooks, although there are also a few contradictions. Previous studies have also indicated that refutational texts particularly support situational model learning and systemic understanding, whereas the learning of facts would be equal regardless of the text type (see Diakidoy et al., 2011; Mikkilä-Erdmann, Penttinen, Anto & Olkinuora, 2008; Penttinen, Anto & Mikkilä-Erdmann, 2013). Further, refutational texts seem to support long-term conceptual change rather effectively, meaning that learning results achieved via refutational texts seem to be relatively stable (see Guzzetti et al., 1993).

Generally speaking, refuting might be a promising tool for developing high-quality science textbooks.

Studying the process of text reading suggests new methods such as eye tracking. Eye tracking allows extremely accurate investigation of the reading process by recording eye movements, for example, during text reading, in relatively authentic conditions. According to the widely accepted eye–mind hypothesis (see Just & Carpenter, 1980), eye movements indicate cognitive processing during the reading process, meaning that there is a close connection between the direction of human gaze and the focus of attention, assuming that the visual environment is relevant to the task at hand (see Hyönä, 2010). Eye tracking is now a relatively common technique used in text reading studies, and the possibilities of this technique have expanded greatly during the last decade due to technological advances (see e.g. Rayner, 1998; Clifton, Staub & Rayner, 2007). For more information about the possibilities of the eye tracking method and how it was utilised in this study, see section 3.2.

1.5 Conceptual change in teacher and medical education

In this dissertation, university students from two different study programs were investigated: future elementary school teachers and medical students. These two study programs were chosen because their structure is similar in many ways. First, both medical and teacher education have a strongly scheduled nature of studying, including a significant amount of independent studying, which is why learning materials play an essential role in studying. Both study programs are multidisciplinary in that they require students to master and work in multiple branches of science (Vilppu, 2016). Second, both professions of doctor and teacher require theoretical understanding and practical skills. In medicine, this means that the education consists of biomedical and clinical studies together with practice, whereas in teacher education the educational sciences and teaching practises should be in active interaction. As scientific knowledge is growing rapidly, both medical and teacher education students are confronted with an overwhelming amount of information, and the need to determine the most relevant aspects in the study material is critical (see Vilppu, 2016). Last, there are a number of conceptual change challenges in these programs related to the learning of biological content.

Both the teaching and medical professions have a strong ethos in Finnish culture. They are also highly appreciated and popular among young people. Only about 15% of applicants are accepted to medical school, and fewer than 10% of applicants are accepted into the teacher education program. These programs have extremely demanding entrance examinations, which necessitates extensive independent studying of various discipline-related topics, such as photosynthesis and the cardiovascular system. Furthermore, the drop-out rate in both study programs is very low. It can therefore be stated that in general, students in the medical and teacher education programs are highly motivated and very talented. Unique characteristics of these study programs related to conceptual change challenges are discussed in detail in the following sections.

1.5.1 Conceptual change demands in teacher education

In Finland, as in many other countries, elementary school teachers are responsible for teaching the science curriculum to children for the first six years of schooling. The need for a better understanding of biological concepts is seen as mandatory for future decision makers to better relate to issues they will encounter for the rest of their lives, such as the loss of fossil fuels, genetic engineering, famine and global warming. In addition, as previous studies have shown that students' conceptions mirror their teachers' ideas, it can be said that the role of elementary school teachers as the shapers of future decisions makers is evident (see Tullberg, Strödahl & Lybeck, 1994).

It is therefore important that classroom teachers master basic knowledge in several scientific fields, such as physics, chemistry and biology, to support high-level learning. However, according to previous studies, it is not only students but also science teachers who have serious misconceptions about basic science phenomena (see, e.g. Papadimitriou, 2004; Treagust & Duit, 2008; Wandersee, Mintzes & Novak, 1994). It can be said that teachers with a poor understanding of central scientific phenomena will have problems providing effective conditions for learning. Furthermore, it is even more harmful if teachers' misconceptions are transmitted to students, as apparently often happens (see, e.g. Tullberg, Strödahl & Lybeck, 1994).

The challenge of teacher education curriculum is that it necessitates students to undergo conceptual changes at several levels that relate to different domains. Current understanding of the development of the teaching profession is based on Schulman's (1987) initial conceptions of the dimensions of content knowledge (CK), pedagogical knowledge (PK) and pedagogical content knowledge (PCK). PK means the broad principles and strategies of classroom management and organisation (Schulmann, 1987). CK in biology constitutes knowledge of the major ideas and theories of a particular domain (e.g. photosynthesis). Furthermore, it incorporates knowledge of how validity or invalidity is established within the domain (i.e., knowledge of research methods) and knowledge of the nature of science (Großschedl, Harms, Kleickmann & Glowinski, 2015).

However, although high CK skills are definitely important for teachers, PCK seems to be at least as important for effective teaching (see, e.g. Baumert, Kunter, Blum, Brunner, Voss, Jordan, Klusmann, Krauss, Neubrand & Tsai, 2010; Großschedl et al., 2015). On one hand, PCK incorporates knowledge of instructional strategies that integrate the representation of subject matter and responses to specific learning difficulties and on the other hand incorporates knowledge of students' preconceptions and typical misconceptions concerning the topic to be learned (Evens, Elen & Depaepe, 2015; Großschedl et al., 2015). Finnish elementary school teachers have a big challenge in mastering the CK and PCK of approximately 12 subjects (see, e.g. Käpylä, Heikkinen & Asunta, 2009). From a university pedagogy point of view, these multifaceted goals related to different competencies important for teachers present extreme challenges for the teacher education curriculum.

1.5.2 Conceptual change demands in medical education

The aim of medical education is to train people to become knowledgeable and responsible medical professionals who are able to update their knowledge and skills continuously during their whole working career as scientific knowledge and medical technology advance. As in teacher education, in medical education the challenge is that when students enter medical school they usually already possess a large amount of prior knowledge consisting of a mixture of formal science knowledge and experimental, informal and even folk knowledge about medical systems and diseases (Boshuizen, Schmidt, Custers & Van de Wiel, 1995). Professors of medicine should therefore avoid the erroneous illusion that because their students have passed an extremely difficult entrance exam and therefore are a select group they have all already constructed an adequate conceptual understanding of the most basic biomedical content. For example, medical students have been found to have persistent misconceptions about certain basic systems, such as respiratory physiology (see Michael et al., 1999) and the CCVS (see Michael et al., 2002).

When it comes to learning medical content, systemic understanding is vital. For example, understanding physiology requires a conceptual understanding of several interrelated systems, which on one hand opens up the potential to form misconceptions (see Fyrenius et al. 2007). On the other hand, the risk that students oversimplify medical information by memorising some facts instead of acquiring a systemic understanding is obvious in a highly loaded curriculum (Modell, 2000; Wilhelmsson, 2010). Furthermore, medical instructors are often unaware that significant misconceptions may occur among students, which makes the teachers unable to support learning effectively (see Michael et al., 1999).

Biomedical knowledge related to clinical reasoning – encapsulation theory

In general, the structure of medical knowledge can be divided into two specific domains. One focuses on biomedical content, such as anatomy, pathology and physiology, and the other deals with clinical aspects, such as the diagnosis, investigation and management of disease signs and symptoms (Donnon & Violato, 2006). Traditional medical curriculum in particular usually consists of two phases, preclinical and clinical, which means that during the first half of medical studies, the aim of the instruction is for students to acquire basic biomedical knowledge. The latter half of medical studies focuses on clinical components, during which students learn clinical skills, such as the treatment and management of diseases, mainly during actual patient encounters. In practice, the physician needs both biomedical and clinical knowledge, which requires that they be integrated (Boshuizen, van de Wiel & Schmidt, 2012).

During the past several decades, there has been an active debate about the role of biomedical understanding in clinical reasoning using different approaches (see e.g. Boshuizen & Schmidt, 1992; deBruin, Schmidt & Rikers, 2005; Feltovich & Barrows, 1984; Kuipers & Kassirer, 1984; Patel, Evans & Groen, 1989; Schmidt & Boshuizen, 1993). It is generally agreed that biomedicine provides a foundation for clinical knowledge (see Kaufman et al., 2008; Woods, 2007). However, previous studies have also shown that experts make little use of biomedical knowledge during reasoning (Boshuizen & Schmidt, 1992; Kaufman et al., 2008). Therefore, Patel et al. (1989) have argued that biomedical knowledge and clinical knowledge can be seen as being worlds apart. Clinical knowledge is mainly used in clinical reasoning, whilst biomedical knowledge is used when backward reasoning exists, for example, when considering the pathophysiology of certain diseases.

In contrast, among medical students, biomedical knowledge seems to play a critical and active role in the clinical reasoning process, especially among intermediate level students (e.g. Patel, Evans & Kaufman, 1990; Van de Wiel, Boshuizen & Schmidt, 2000). Therefore, as expert medical practitioners do not actively seem to use biomedical knowledge in reasoning, it has been assumed to affect their reasoning processes at an automated level (Schmidt & Boshuizen, 1993). According to encapsulation theory, during medical studies biomedical knowledge gradually becomes packed or encapsulated, whereby lower-level details and interrelations are organised under upper-level concepts (see Schmidt & Boshuizen, 1993; Schmidt & Rikers, 2007; Van de Wiel et al., 2000). As medical students begin to use this encapsulated biomedical knowledge in encounters with patients, the encapsulated biomedical knowledge and clinical experience transform into narrative structures called *illness scripts* (see, e.g. Feltovich & Barrows, 1984; Schmidt & Rikers, 2007; Charlin, Boshuizen, Custers & Feltovich, 2007).

Illness scripts consist of *enabling conditions* for a certain disease, *the consequences* of that disease and the *biomedical fault* that explains how the enabling conditions can lead to consequences (Boshuizen et al., 2012; Feltovich & Barrows, 1984). Illness scripts help doctors find patterns of diseases, filter out irrelevant information and construct working hypotheses effectively (Boshuizen et al., 1995). The effective use of illness scripts enables experts to make diagnoses much faster compared to less experienced medical students. For example, experienced practitioners make better use of predisposing factors compared to novices (e.g. Schmidt & Rikers, 2007), and therefore enabling factors act as effective promoters of illness script activation for them. While solving problems, physicians search for an appropriate script, and when they have selected one or a few, they will then match the elements to the information provided by the patient in a so-called script-verification process (Boshuizen et al., 1995). Overall, the role of biomedical knowledge in clinical reasoning seems to gradually change during medical education. Researchers have different views about how biomedical knowledge is involved in the clinical reasoning process, but there are only few studies concerning the diagnosing process at the level of eye movements.

2. AIMS

The general aim of the present thesis is first to explore which kinds of conceptions and potential misconceptions exist about photosynthesis among teacher education students and about the CCVS among medical students. If misconceptions still exist, it must be determined what they are, what consequences they have for systemic understanding and clinical reasoning and how they evolve on one hand in relation to the progress of studies and on the other hand to different learning materials. These aspects were investigated, thus extending the view from the group level to the single case level (Figure 4).

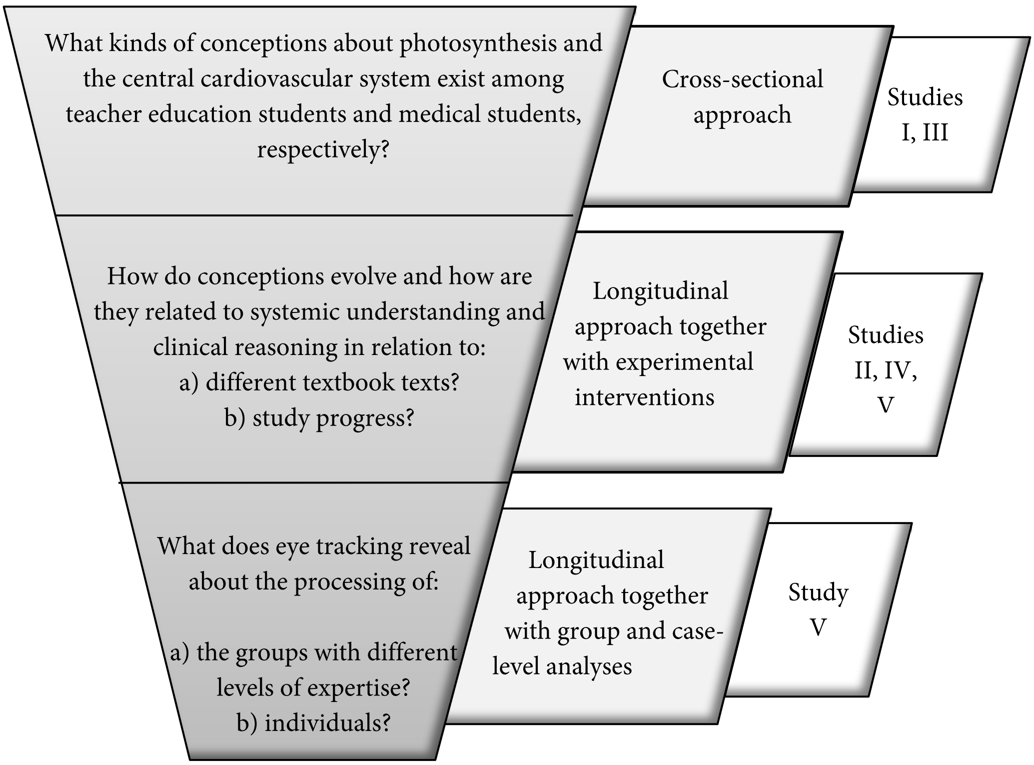

Figure 4. The research scope.

The specific objectives of the five studies discussed in this dissertation were as follows.

1) The purpose of Study I was to investigate what kinds of prior conceptions teacher education students have about photosynthesis and how participants' conceptions change after reading an expository text on photosynthesis. We were also interested in how participants' learning goals were related to learning outcomes. The broader purpose of this study was to develop tasks and the text for the next study phase (Study II).

2) The first aim of Study II was to deepen the understanding of teacher education students' misconceptions of photosynthesis on the systemic level. The second aim was to determine the role of a refutational text based on previously detected misconceptions in guiding science learning.

3) Study III started the series of studies on medical context. The purpose of this study was to determine what kinds of prior conceptions first year medical students have about the CCVS. We developed and piloted a biomedical task concerning the CCVS for future purposes.

4) The aim of Study IV was to follow-up how the level of biomedical understanding of the CCVS develops during the preclinical phase in medical education. We were also interested in how the level of biomedical understanding is related to success in the clinical reasoning task.

5) The purpose of the Study V was first use the eye-tracking method to investigate the reading processes of medical students and internal medicine residents when they read a patient case. Second purpose was to follow-up certain Study IV participants to investigate whether the level of biomedical understanding in previous study years is related to success in the diagnosing task. Both case-based and group-level analyses were accomplished using a longitudinal approach.

3. METHODS

3.1 Participants

The participants were native Finnish speaking university students from two different study programs, medicine and teacher education. The data was collected between 2008 and 2012. Participation in all studies was voluntary, and informed consent was obtained. The participants in Study I (N = 18) and Study II (N = 91) were second-year student teachers from one Finnish university in 2008–2009. The participants in Study III, Study IV and Study V were medical students from one Finnish university. The participants in study III (N = 60) were first-year medical students in 2008. One cohort of medical students was followed during their first study years in Study IV (N = 119) and Study V (N = 33) from 2009–2011. A total of 13 (N = 13) internal medicine residents from one Finnish university hospital participated in Study V in 2012 as a control group. Approval was obtained from an ethics review board for studies with a medical context.

3.2 Materials, data collection procedures and analysis

The empirical studies of this dissertation are based on five different data sets. Table 1 summarises the participants, materials and analyses used in each study.

Table 1. Summary of methods.

Study	Participants	Materials	Analyses
Study I	2nd year student teachers, *n* = 18, Cohort α	Written open-ended tasks concerning photosynthesis Assessment of learning goals An expository text concerning photosynthesis	Qualitative and quantitative analyses Conceptual map tool Repeated measures t-test
Study II	2nd year student teachers, *n* = 91, Cohort β	Written open-ended tasks concerning photosynthesis An expository and refutational text concerning photosynthesis	Qualitative and quantitative analyses Conceptual map tool Independent samples t-tests Repeated measures t-test.
Study III	1st year medical students, *n* = 60, Cohort α	Written open-ended drawing task concerning the CCVS	Qualitative and quantitative analyses
Study IV	1st and 2nd year medical students, *n* = 119, Cohort β (followed in 2009–2010)	Written open-ended tasks concerning the CCVS Written open-ended clinical reasoning task Multiple-choice questions	Qualitative and quantitative analyses Conceptual map tool Independent samples t-tests Repeated measures ANOVA Correlation analyses
Study V	3rd year medical students, *n* = 33, Cohort β (followed in 2009–2011) Internal medicine residents, *n* = 13	Written patient case concerning pulmonary embolus Verbal and literal reports Scores of medical entrance exam. Multiple-choice questions concerning the CCVS Additional data from Study IV	Qualitative and quantitative analyses Categorisation of literal reports for relevant/ irrelevant aspects Mann–Whitney U tests Kruskal–Wallis tests

Studies I and II

In Studies I and II, a pretest-posttest design together with a delayed posttest were employed. The tests were written open-ended questions and concerned photosynthesis from varying perspectives. There were factual questions (e.g. *Explain the terms a)* *autotrophic b) heterotrophic*), questions that measured text comprehension (e.g. *What is the role of plants in food chains? Why?*) and generative questions (e.g. *How do a dandelion, an earthworm (herbivore) and a mole (insectivorous) get their a) nourishment b) other vital things?*). The questions were the same in each time of measurements, and in the posttest, participants had the chance to compare and revert to his/her pretest answers. There were no time limits to answer the questions or do the reading.

In Study I, after answering pretest questions, the participants' learning goals related to photosynthesis were examined by asking them to write things down and asking them what they would like to learn about photosynthesis. In Studies I and II, the role of different text types in guiding learning was inspected. The texts all dealt with photosynthesis and were designed in the research group. In Study I, there was a traditional, expository text and in Study II, an expository text and a refutational text were compared. In Study II, the texts were identical except for two additional refuting paragraphs concerning the concept pairs of energy versus matter and nutrients versus nourishment in the middle of the refutational text (Figure 5).

Food chains illustrate how energy flows from one organism to another. Carrot leaves bind solar energy in the process of photosynthesis, a rabbit gets part of this energy by eating the carrot and, in turn, a fox gets part of this energy by eating the rabbit. In each phase, some portion of the energy leaves the food chain. Thus, only small amount of the energy the carrot originally photosynthesized ends up in the fox.

Energy does not cycle in the food chain but enters the food chain only by photosynthesis. Loss of energy from the food chain means that a carnivore at the top of the food chain consumes much more energy for its growth than a same-sized herbivore would need, because of more steps in the food chain. In the food chain, matter cycles and returns from the top of the food chain to the photosynthesizing organisms. When a dead organism decomposes, nutrients from it are released back to the soil. Plants can use these nutrients again when they grow and photosynthesize.

Concepts of matter and energy are often confused. Matter cycles in nature so that when a dead animal decomposes, nutrients are released back to the soil. Many people think that energy also cycles in nature, but this does not happen. Energy has to continuously flow to the food chain. For this, photosynthesizing organisms are needed, because they are able to change solar energy to chemical energy for other organisms to use.

Figure 5. An example from the texts in Study II. The last paragraph was present only in the refutational text and is italicised to highlight it. The section discusses food chains, energy and matter.

The data from Studies I and II were analysed using qualitative and quantitative methods. Conceptual map kinds of tools of photosynthesis were constructed and used as analysis tools to assess participants' systemic understanding of photosynthesis.

Using a conceptual map tool, the participants' representations could be scored by counting correct (+2 p), simplified (+1 p) and false links (-2 p) between the concepts. An interrater assessment was made for 20% of the data to guarantee the reliability of the analysis and the interrater reliability of 73% was achieved in Study 1 and 81% in Study II. In Study I, the students' learning goals were categorised into three groups targeting either factual or systemic understanding or no specified goals at all. In Study II, the participants' pretest representations were categorised as scientific, moderate or naïve based on participants' understanding of the most important link between the concepts of photosynthesis and nourishment. The scores of the different groups were compared using statistical analyses.

Study III

In Study III, a pretest–posttest design was used, where a written assignment about the CCVS was repeated before and after a two-month course dealing with blood circulation, respiration and fluid balance. The open-ended task before and after the course was: *Draw and explain the central cardiovascular system and blood flowing in it.* The data was analysed using qualitative and quantitative methods. At first, the participants' representations were classified into two groups, scientific or naïve. Naïve representations were classified further into models with factual errors and models with misconceptions or serious deficiencies. The interrater reliability of the classification performed by two researchers was 83.3 %, and after negotiation it was 100%.

Study IV

In Study IV, a pretest–posttest design was employed, where a written assignment about the CCVS was repeated before and after a six-week course dealing with blood circulation, respiration and fluid balance. The repeated task was: a) *Draw the structure of the central cardiovascular system (the heart with the largest vessels). Name the structures.* b) *Explain how the blood flows in the structures you drew*. There were also two multiple-choice questions about the timing of the right and left ventricular contractions (*the right ventricle of the heart contracts a) before b) after c) at the same time as the left ventricle*) and the oxygen content of the blood flowing in the pulmonary veins (*the pulmonary veins bring a) oxygen-rich blood from the lungs to the heart b) oxygen-poor blood from the heart to the lungs c) oxygen-rich blood from the heart to the lungs*).

In the second year, the participants' representations of the biomedical content of CCVS were examined again, this time with two written assignments. The first task was: *Explain the path of a red blood cell from the left ventricle back to the same place.* Also included was a figure task concerning the pulmonary circuit. In the figure task, the participants were given a scheme of the pulmonary circuit and were asked to add arrows between the anatomical structures to indicate how the blood flows in the pulmonic circulation. The students were instructed that the number of arrows symbolised the number of the blood vessels, for example, from the right ventricle via two pulmonic arteries to the lungs (one per lung) and from there via four pulmonic veins (two per lung) to the left atrium. The students were asked to mark the arrows with either a broken line to indicate oxygen-poor blood or an unbroken line to indicate oxygen-rich blood. In addition to biomedical tasks, the follow-up study included a written clinical task concerning varicose veins and oedema in legs. The questions were: a) *Why does a patient with varicose veins often suffer from oedema in the legs?* b) *Explain the mechanism of oedema*. The clinical task suggested the application of biomedical knowledge.

The data of biomedical tasks was analysed using analysis tools and was quantified to compare the scores of different times of measurements. An interrater assessment was made for 20% of the data to guarantee the reliability of the analysis and the reliability was found to be 96%. The answers to the clinical task were scored. Statistical analyses were conducted to investigate the development of biomedical knowledge and its relationship to success in the clinical reasoning task.

Study V

In Study V, the reading of a written patient case text in relation to the level of eye movements was investigated using a Tobii T60XL Eye Tracker (Tobii Technology, Inc., Falls Church, VA, USA). To do this, infrared cameras tracing the position of the participants' pupils were integrated into the body of a high-resolution 24" computer monitor operating at 60 Hz with a resolution of 1,920 x 1,200 pixels on which the stimuli were presented. The accuracy of the eye tracker was 0.6° in ideal conditions. Because the Tobii T60XL Eye Tracker allows even large head movements and the reading process needed to be kept as realistic as possible, no supporting chin rests were used. Thus, the research was carried out in relatively authentic conditions.

The patient case text about pulmonary embolus was 225 words long. It was in the form of a PowerPoint presentation, and the font used was 17 pt Arial. The text was designed by the research group and was evaluated by two cardiology specialists. The text followed the format of a typical patient case and included an anamnesis (slide 1), status (slide 2) and examination results, such as laboratory tests and X-rays of the patient (slide 3). The sentences in the text were categorised into three groups: key sentences (included essential information of the case that guided readers towards the correct diagnosis), supplementary sentences (supported the reader to exclude incorrect options) and irrelevant sentences (contained irrelevant information). After each slide, there were written questions for the students and oral questions for the residents (the purpose of the difference was only to save the residents' time, as they were participating in the study during their busy working hours). After the anamnesis, the question was: *Name the most important symptoms according to the anamnesis*. After the status, the participants were asked to answer the question: *Name the most essential findings according to the patient's status*. Finally, after the last slide, there was the question "*Give a diagnosis and name the most important symptoms and findings based on* the diagnosis determined. After reading the patient case, the participants were verbally asked to outline from the text those aspects based on what s/he made the diagnosis.

The students' level of biomedical understanding of the CCVS was measured using multiple-choice questions before the laboratory study phase. The information concerning the students' level of biomedical understanding of the CCVS from previous years was available from Study IV. Based on the given diagnosis, the participants were divided into a correct diagnosis group and an incorrect diagnosis group. The eye-tracking data, more specifically the processing times and total visit durations, were investigated using Tobii Studio eye-tracking software and examined using non-parametrical statistical analyses. The medical entrance exam scores and longitudinal data about the development of biomedical understanding of the CCVS were used as background variables.

Conceptual map as an analysis tool to measure systemic understanding

In Studies I, II and IV, qualitative analysis was accomplished using conceptual mapping tools adapted for the research purposes. This approach enabled us to effectively evaluate what kind of representation each participant had constructed of the whole system and to detect for which part of the system the possible misconceptions and deficiencies had occurred. The idea was to visualise the participants' representations based on the answers to the open-ended and multiple-choice questions by adding different coloured links between the concepts of the phenomenon. Different coloured links (correct conception: green link; simplified, not a false conception: yellow link; missing link: 0 points; misconceptions: red link) were scored differently in different sub-studies. Inter-rater reliability analysis was accomplished for 20 % of each data set, and acceptable inter-rater percentages of 73–96 were determined.

In several previous studies (see e.g. Kinchin, 2000b), the systemic nature of a certain scientific theme is represented using a conceptual mapping approach. Concept mapping was originally developed as a pedagogical tool in the 1980s in the course of research conducted by Joseph D. Novak to describe explicit changes in children's conceptual understanding and to represent relationships between relevant concepts within a given subject area (Novak & Cañas, 2006). There are different interpretations concerning conceptual maps in the literature, but typically they are constructed so that one core concept is presented in a box in the middle of the paper with lines showing linking words that create a meaningful statement or proposition. Concepts may be arranged hierarchically so that the most general, most inclusive concepts are at the top and the most specific, least general concepts are at the bottom (Novak & Cañas, 2006). Conceptual maps have been successfully used to facilitate learning or as assessment or analysis tools at several educational levels over the last few decades (see e.g. Brandstädter et al., 2012; González, Palencia, Umaña, Galindo & Villafrade, 2008; Kinchin, 2000a, Nesbit & Adesope, 2006; Novak & Cañas, 2006; Ratinen, Viiri & Lehesvuori, 2013). In the studies of this dissertation, the use of adapted conceptual maps in analysing the data enabled a deep understanding of the participants' representations of the topic at hand.

Eye tracking method in studying the learning process in medical context

In Study V eye tracking method together with complementary methods was accomplished in order to gain better understanding of participants' processing of a patient case. In order to understand better characters of students' processing, internal residents were used as a control group.

The reading process is known to consist of fixations, during which the eyes are relatively still, and saccades, which are rapid eye movements between the fixations. According to current understanding, information is gathered only during fixations (Rayner, 1998; 2009). To date, eye tracking has provided interesting insights into how experts differ from novices when processing tasks with a high visual component (see Charness, Reingold, Pomplun & Stampe, 2001; Jarodzka, Scheiter, Gerjets & van Gog, 2010). Being expert in medicine means that one is able to consistently produce better treatment outcomes and more accurate diagnoses even in adverse conditions compared to less experienced actors (Ericsson, 2007). For example, when comparing the processing times in different domains, experts have been found to spend less time on tasks compared to novices (see e.g. Gegenfurtner, Lehtinen & Säljö, 2011; Mann, Williams, Ward & Janelle, 2007). In the medical domain, the evidence suggests that experts are able to detect, for example, anomalies in X-rays significantly faster compared to those with less experience (Kundel, Nodine, Conant & Weinstein, 2007). This is explained by experts' superior speed in processing information (Ericsson & Kintsch, 1995; Haider & Frensch, 1999) and their higher level of confidence (Nodine, Mello-Thoms, Kundel & Weinstein, 2002). Another interesting finding is that experts fixate more on task-relevant areas than task-redundant areas, meaning that they are able to find relevant aspects of the stimulus more effectively compared to novices who often fixate equally on both task-relevant and task-redundant areas (Gegenfurtner et al., 2011). This has been explained with the information-reduction hypothesis (Haider & Frensch, 1999), according to which the experts are able to ignore task-redundant information and focus on task-relevant aspects remarkably more efficiently compared to others during reading.

When complex cognitive processes are studied using the eye-tracking method, complementary methods are also needed to explain the reading behaviour (Hyönä, 2010). Even though this method provides highly valuable information about subjects' eye movements, it does not by itself tell the researcher anything about success or failure in comprehending relevant pieces of information (Hyönä, 2010). Further, the part of the text that may seem to attract participants' attention may include confusing and problematic information or especially interesting information; both interpretations are common in eye-tracking studies (see Hyrskykari, Ovaska, Majaranta, Räihä & Lehtinen, 2008). Useful methods of complementing eye-movement data include different stimulated retrospective recall or think-aloud protocols. The purpose of these incorporating these methods is to gain deeper insight into participants' cognitive processes during or after the intervention.

4. OVERVIEW OF THE EMPIRICAL STUDIES

4.1 Study I

Ahopelto, I., Mikkilä-Erdmann, M., Anto, E., & Penttinen M. (2011). Future Elementary School Teachers' Conceptual Change Concerning Photosynthesis.
Scandinavian Journal of Educational Research, 55 (5), 503–515.

Previous studies have shown that photosynthesis is a difficult topic to learn at several educational levels from primary school to higher education. Based on their prior framework theories, students may have existing inaccurate conceptions that might hinder the proper understanding of various science concepts. However, understanding, for example, serious environmental problems such as climate change necessitates knowing the basics of photosynthesis. The role of elementary school teachers as shapers of future decisions makers is evident because they are responsible for teaching the science curriculum to children during their first six years of schooling. It is therefore important that teachers themselves have a correct understanding of this most important topic. Therefore, the aim of this study was to determine what kinds of prior conceptions future elementary school teachers have about photosynthesis before a text reading and how their conceptions change after reading an explanatory scientific text on the topic. Students' learning goals were also examined in relation to learning outcomes.

The participants (N = 18) were second year teacher education students from the Department of Teacher Education at a Finnish university. The study employed a quasi-experimental pretest–posttest design with a delayed posttest. The measurements included an open assessment of participants' learning goals related to the topic and nine open-ended written questions of varying difficulty about photosynthesis presented before and after the text reading (for more detailed information about the tasks and analyses, including examples, see section 3.2.). A delayed posttest (N = 12) was conducted seven months after the study.

The results showed that every participant but one had taken the compulsory courses in biology and that they had relatively low scores in the pretest, which indicated deficiencies in understanding the theme of photosynthesis. Half of the participants (n = 9) had clear misconceptions about photosynthesis, as they answered that plants take their nourishment ready-made from the soil. However, in the posttest, none of the participants had misconceptions about the nourishment supply of plants; however, five presented a synthetic representation. Overall, participants' scores increased remarkably after reading the text. In the delayed posttest, participants' scores decreased relatively little, but most of the students stayed with a mainly scientific model after seven months of text reading.

Most of the students (n = 11) expressed low-level learning goals targeted at learning factual things about photosynthesis. Only four participants aimed to acquire a systemic understanding of photosynthesis. High-level learning goals predicted high-level learning outcomes, and three of the four participants who aimed at to acquire a deeper understanding underwent a conceptual change, whereas only one of those who aimed to learn more factual things about photosynthesis (n = 11) underwent a conceptual change.

Generally, our study shows that future elementary school teachers have serious difficulties in understanding the important topic of photosynthesis. However, a coherent explanatory text seemed to act as an effective support in learning. Further, the results indicate the important role of intentionality in the process of conceptual change. Although the sample size in this study was small, these results provide important information about university students' misconceptions about photosynthesis, which supported the development of texts and questions for forthcoming studies.

4.2 Study II

Södervik, I., Mikkilä-Erdmann, M., Vilppu, H. (2014). Promoting the Understanding of Photosynthesis among Elementary School Student Teachers through Text Design.
Journal of Science Teacher Education, 25, 581–600.

As the results of the Study I and certain other previous studies revealed, misconceptions about photosynthesis seem to be common among preservice student teachers. The aim of this study was to deepen the understanding of student teachers' conceptions about photosynthesis and to investigate if a refutational text could support learning more effectively than a traditional, expository text. We also examined if the refutational text facilitated systemic understanding better than an expository text and whether the level of prior knowledge was connected to better learning results using either a refutational or an expository text.

The participants (N = 91) were second year student teachers from the Department of Teacher Education at a Finnish university. The students were randomly assigned to two different text groups; half of the students (n = 45) read a refutational science text about photosynthesis and the other half (n = 46) read a non-refutational text. The study consisted of a quasi-experimental pretest–posttest design, and eight open-ended written questions of varying difficulty about photosynthesis were presented before and after reading the text. The texts in both groups were identical except for two additional refuting paragraphs in the middle of the refutational text. (For more detailed information about the tasks and texts, including examples and analyses, see section 3.2.) A delayed posttest was conducted two weeks after the study.

Overall, the results alarmingly showed that participants had clear difficulties in understanding photosynthesis in the pretest. It was also found that a refutational text seemed to support learning more effectively than a traditional text. The experimental group outperformed the other group in answering the questions measuring both factual and systemic understanding of photosynthesis. The refutational text particularly helped those participants who presented naïve representations in the pretest. In addition, the participants' scores remained rather high in the delayed posttest, although the decrease compared to the posttest scores is significant. Therefore, a refutational text can be an effective facilitator of conceptual change in science classrooms, especially for those students who have prior misconceptions about the phenomenon.

4.3 Study III

> Mikkilä-Erdmann, M., Södervik, I., Vilppu, H., Kääpä, P. & Olkinuora, E. (2012). First-year Medical Students' Conceptual Understanding of and Resistance to Conceptual Change Concerning the Central Cardiovascular System.
>
> *Instructional Science*, 40, 745–754.

Previous studies have revealed that understanding certain biological content, such as the CCVS, is difficult for students at different educational levels. However, there are relatively few existing studies about this theme at the university level. The aim of this study was therefore to investigate whether there still exists misconceptions about the CCVS among first-year medical students who have passed an extremely difficult entrance exam. We also investigated how these conceptions change after an actual cardiovascular course.

The participants were 60 first-year medical students at a Finnish university. The study was based on a pretest–posttest design. Both the pretest and the posttest consisted of an open-ended drawing task, in which students were asked to draw and write an explanation of the relevant components of the CCVS (the heart and the largest blood vessels) and blood circulation within the structures (for information about the actual assignments, see section 3.2.). The participants took a seven-week course on blood circulation, respiration and fluid balance between the pretest and the posttest.

The results showed that almost half of the medical students (n = 37) presented more or less incomplete representations of the CCVS before the course. Of these students, 17 had misconceptions or serious deficiencies in their representations. The most typical misconception was the 'serial loop' misconception, which means that the double-loop function of the circulatory system was poorly understood. After the course, 54 of the 60 students described a scientific model of the CCVS. However, six students still had serious misconceptions, four of which were related to the serial loop idea. This result is extremely worrying because we argue that medical students should have the goal of mastering at least the very basic biomedical content. Even one student with misconceptions about this important topic is too many. Therefore, although the instruction seemed to be effective for most of the students, there is still work to do to advance science education in medical education. The results of this study were used in developing experiments for forthcoming studies.

4.4 Study IV

Ahopelto, I., Mikkilä-Erdmann, M., Olkinuora, E. & Kääpä, P. (2011). A Follow-up Study of Medical Students' Biomedical Understanding and Clinical Reasoning Concerning the Cardiovascular System.
Advances in Health Sciences Education, 16, 655–668.

According to previous research and the results of Study III, novice medical students often hold initial conceptions about biomedical content that may hinder learning. Therefore, the purpose of this study was to investigate what kinds of biomedical representations medical students constructed about CCVS in their first and second years of study and how the quality of these representations was related to their success in the clinical reasoning task.

The participants were 119 medical students from a Finnish university. In the first study year, the study was based on the pretest–posttest design with a course on the cardiovascular system between the tests. The measurements were a drawing task about the structures of the human heart and the blood flowing in the heart and two multiple-choice questions to complete the drawing task. In the second study year, the students' representations of the CCVS were re-examined with two written assignments to determine changes in the level of their biomedical understanding. Further, the level of clinical reasoning related to the CCVS topic was measured with a written clinical task about varicose veins and oedema in the legs. Data from the biomedical tasks in both years were analysed quantitatively using a conceptual map analysis tool and then quantified. This analysis method enabled us to compare the level of students' biomedical knowledge in both years. The answers to the clinical task were scored. (For the actual assignments in each study year and analyses, see section 3.2.)

Overall, the results showed that although medical students achieved relatively high scores in the biomedical task, half of them had one or more misconceptions before the cardiovascular course. Certain of these misconceptions were extremely serious. After the course, the scores were statistically higher, and less than one-third of the students had misconceptions. In addition, the level of clinical reasoning seemed to be related to the increase in the level of biomedical knowledge. It became apparent that those students who had low scores on the biomedical assignments in the second year also had lower scores on the clinical task. Further, those students who achieved excellent scores in the clinical task increased their biomedical understanding significantly between the first and second year of study compared to those with poorer clinical reasoning skills.

Therefore, the results highlight the role of biomedical understanding during early medical studies. The results also raise the important issue of how to help medical students become aware of their naïve ideas and to help then construct scientific understanding more effectively. Medical educators should be aware of students' potential misconceptions related to biomedical content and of the connection between the level of biomedical knowledge and clinical reasoning.

4.5 Study V

Södervik, I., Vilppu, H., Österholm, E. & Mikkilä-Erdmann, M. (*in review*). The Relationship between Biomedical and Clinical Understanding in Medical Students and Residents – Combining Eye-tracking and a 3-year Follow-up.

During the last several decades, there has been active research aimed at understanding how medical students acquire high competence during medical education on their way to medical expertise. It has been suggested that during medical studies, biomedical knowledge is encapsulated together with clinical experience to form so-called illness scripts. Therefore, this study follows up certain Study IV participants with the aim of deepening understanding about the development of medical expertise. The specific object of this study was to compare the reading processes of medical students and residents when they read a patient case about pulmonary embolus. We were interested in how medical students and residents find the relevant information from the text. We compared the students' level of biomedical understanding of the CCVS in previous study years with their success in the clinical diagnosis task.

A total of 33 third-year medical students from a Finnish university and 13 internal medicine residents from a university hospital participated in this study. All the participants read a short patient case relating to pulmonary embolus from a computer screen, during which their eye movements were recorded. The topic of the case was chosen based on the fact that it would be familiar to the students and that knowing the pathophysiology of this condition necessitates understanding of the CCVS. (For more detailed information about the equipment, the patient case text, the assignments and the analyses, see section 3.2.)

The results showed that 15 of the 33 medical students and all the residents gave a correct diagnosis after reading the patient case. Generally, as presumed, the residents read the case significantly faster compared to the students. However, regarding the very first key sentence of the case relating to enabling factors, there was not a significant difference in fixation durations between the residents and the students. This sentence might have activated residents' illness script pattern, an interpretation that was also supported by interviews. Overall, those students who gave a correct diagnosis read the text faster and found more relevant aspects compared to those who failed to give the correct diagnosis. When compared to the longitudinal data concerning the biomedical understanding, our results interestingly showed that the level of biomedical understanding was generally higher among students who diagnosed the patient case correctly. However, the results were not statistically significant.

In summary, activation of the illness script pattern might be reflected by the duration of fixations on the enabling factors a patient case. Therefore, we suggest that teaching 'illness script grammar' should be part of medical education. For example, an expert's pattern during the reading of a patient case text could be used as a learning tool to highlight the importance of the anamnesis phase in diagnosing. In addition, this study highlights the importance of biomedical knowledge in developing medical expertise.

5. DISCUSSION

5.1 Main findings

This thesis contributes to domain-specific science learning research at the university level and is based on the research traditions of conceptual change and science learning and teaching. As previous research has shown that students at different educational levels have misconceptions about complex scientific phenomena, the purpose of this thesis was to investigate teacher and medical education students' conceptions about certain biological phenomena that are central in their curriculum, namely photosynthesis and the cardiovascular system. Our aim was to investigate how learning could be supported via different kinds of texts, such as refutational texts, specifically designed to support the learning of a particular concept. We employed a longitudinal approach to determine how future doctors' biomedical understanding develops during medical studies and how the level of biomedical knowledge is related to success in clinical reasoning tasks, such as diagnosing a patient case. The eye-tracking technique was used to compare the reading processes of medical students and internal medicine residents while reading a patient case text.

The most important findings of this thesis are as follows: **(1)** Misconceptions about the central scientific phenomena of photosynthesis and the cardiovascular system are common among future teachers and doctors. The misconceptions were unexpectedly serious and to some extent similar to those found in previous studies of misconceptions among children. Certain misconceptions remained after instruction. **(2)** The refutational text promoted learning about photosynthesis more than a traditional, expository text. In particular, those students who had a naïve conception of the phenomenon before the intervention benefitted more from the refutational text. Further, the refutational text facilitated both factual and systemic understanding more than the expository text. **(3)** In medical learning, high-level biomedical understanding indicated to interrelate with success in clinical reasoning among second and third year medical students. **(4)** Medical residents generally processed a written patient case text faster than medical students. Those students who diagnosed the patient case correctly read faster than those who failed to give a correct diagnosis. The next finding perhaps explains this difference in total visit durations. **(5)** Eye movements together with complementary data indicate that an illness script pattern might be distinguishable in the processing of medical residents and successful students. Overall, eye tracking seems to be a promising method not only for examining the development of medical expertise but also for advancing more effective learning materials at the university level.

5.1.1 Understanding photosynthesis is demanding – high-level text can support learning

Finnish elementary school teachers are highly qualified; they have passed a very difficult entrance exam, and there is a basic requirement for a master's degree for classroom teachers. However, although teacher education students are a talented and motivated group of learners, our results (Studies I and II) unfortunately indicate that future elementary school teachers' understanding of one of the most important biological phenomena, photosynthesis, was relatively poor before text interventions. This result is alarming, even though it is in line with the results of previous studies in which student teachers are reported to hold misconceptions about other complex biological phenomena also, such as greenhouse effect (see e.g. Ratinen, 2013) and cellular respiration (Brown & Schwartz, 2009).

Teachers' misconceptions related to scientific content pose problems for science learning on at least two levels. Children typically have several misconceptions based on their framework theories of naïve biology when they enter elementary school (see Carey, 1985; Inagaki & Hatano, 2013; Vosniadou, 2013), and teachers who themselves have a poor understanding of the central biological phenomena will have difficulty recognising these misconceptions and designing their teaching accordingly. Therefore, it is harmful if children's naïve ideas are either actively or passively supported during the early school years. Further, previous studies have shown that students' conceptions mirror their teachers' ideas, which means that in the worst case a teacher's misconceptions may be transmitted for students, as apparently sometimes happens (see e.g. Tullberg, Strödahl & Lybeck, 1994).

In addition, teachers who have a poor understanding of certain key concepts will presumably have difficulty providing learning environments that will lead to systemic understanding on a larger scale. This could mean that when studying photosynthesis, the interrelations between different topics, such as photosynthesis and climate change or photosynthesis and cellular respiration, that are typically handled separately in both science classrooms and learning materials are therefore understood only superficially (see also Brown & Schwartz, 2009). Further, systemic learning could be supported by discussions about the meaning of photosynthesis for life on Earth using concrete examples (e.g. encouraging students to consider how energy ends up in food, such as in tomatoes or meat that one eats). Because the quality of instruction plays a key role in learning (see e.g. Kuijpers, Houtveen & Wubbels, 2010), it should be a minimum requirement that future elementary school teachers have a solid scientific understanding of at least the most central scientific phenomena to help children construct systemic understanding of biological phenomena.

The role of learning material is essential in supporting conceptual change in science classrooms. Nevertheless, there is relatively little science learning material at the higher education level for student teachers. Study II indicated that a text specifically tailored to facilitate learning about photosynthesis helped learners understand this complex topic. Further, a refutational text supported learning more effectively than a traditional expository text. This result is in line with several earlier studies that have proven that refutational texts facilitate the learning of complex scientific phenomena more effectively than traditional expository texts (for a review, see Tippett, 2010). According to Hynd (2001), the superiority of refutational text in supporting conceptual change is based on its ability to induce dissatisfaction with one's previous conceptions that contradict with the explained scientific view (see also Posner et al., 1982). In addition, besides causing dissatisfaction, a refutational text explains the scientific concept clearly and in depth, making it plausible for the reader through believable examples. Finally, a refutational text shows the usefulness and the explanatory power of the new concept. In short, refutational text meets all four conditions for conceptual change that are outlined in Posner et al.'s (1982) well-known model (Ariasi & Mason, 2011). Broughton et al. (2010) hypothesise further that the refutation effect may result from co-activation, from the integration of prior conceptions with the new information (see Kendeou & van den Broek, 2007) and from increasing the learner's engagement with the text (Dole & Sinatra, 1998).

Our results support the important finding that students with weaker existing knowledge benefit from refutational texts more than from expository texts (see also Diakidoy et al., 2011; Kendeou & van den Broek, 2007). This result highlights the possibilities of refutational texts to assist students with weaker knowledge in revising their prior conceptions. Interestingly, unlike in several previous studies (see e.g. Alvermann & Hague, 1989; Diakidoy et al., 2011; Mikkilä-Erdmann, 2001), our results also showed that refutational texts supported both systemic and factual understanding more than a non-refutational text. We suggest that a refutational text may encourage readers in terms of active reflection and critical reading in general, which again would support overall learning (see Wellington & Osborne, 2009).

However, it must be noted here that findings concerning the effectiveness of refutational texts have are not consistent across studies with different measurements, topics and samples (see Diakidoy et al., 2011). For example, previous research has shown refutational texts to be more helpful with samples of high-school and college students than elementary school students (Diakidoy et al., 2003; Broughton et al., 2010). This presumably is because older learners are usually better able to reflect on their own understanding than young children and therefore older students' metaconceptual awareness is suggested to be higher compared to small children. Furthermore, refutational texts have been criticised for being authoritative or anti-constructivist in the sense that they neither let the reader discover for themselves nor encourage critical thinking (Hynd, 2001). However, instead of only trying to get students to revise their misconceptions, the broader goal of refutational texts should be to encourage readers to critically weigh their own conceptions against the scientific view, that is, to facilitate metaconceptual awareness and to help students to understand what they are experiencing when being persuaded to adopt a particular scientific view (see Hynd, 2001).

We suggest that refutational texts should be studied in more depth using process methods such as eye tracking to gain a better understanding of what happens in terms of eye movements when one reads text that systematically highlights typical misconceptions beside a scientific explanation and thus what exactly the refutation effect is. To conclude, refutational texts seem to offer potential in terms of providing an effective and economical way of supporting conceptual change in science classrooms, especially in higher education. This is an important finding from the university pedagogical point of view.

5.1.2 Understanding biomedicine is challenging but essential for clinical reasoning

The explosion of knowledge is a reality in medical education, and medical schools are confronted with the challenges of introducing new core knowledge into an increasingly crowded curriculum (Kaufman et al., 2008; Michael, Modell, McFarland & Cliff, 2009). Medical students have passed an extremely difficult entrance exam, which necessitates a lot of independent studying of biomedical content. Therefore, when students begin medical studies, they already have a quite a lot of knowledge of basic biomedical concepts. For that reason, medical instructors may have a faulty belief that all medical students had already constructed an adequate understanding of basic biomedical content before entering medical school. This may encourage medical educators to focus on more complex content, such as clinical topics, instead of basic content (see Kaufman et al., 2008).

Our research revealed that medical students have a substantial number of serious misconceptions related to one very basic topic in their curriculum, the CCVS (Studies III and IV), and that certain misconceptions also remained after the instruction. These results are in line with previous studies that have reported difficulty in learning about the CCVS (see e.g. Chi, 2005; Michael et al., 2002) and respiratory physiology (see e.g. Michael et al., 1999). Certain of these misconceptions, especially the ideas of a 'single pump' and 'serial loops'—which both deal with the fact that in the circulatory system there is not one but two simultaneously acting paths—may partly derive from the fact that information about the circulatory system is often mainly derived from textbooks. For practical reasons, traditional textbooks present simultaneous processes individually and highlight the direct nature of this content. Often, the circulation path is presented and numbered in a serial fashion to make the content more easily understood, but actually this manner of representation unintentionally highlights the circulatory system as a one-path model.

Systemic understanding necessitates knowing the interrelationships between factors or aspects. For example, when studying the heart, both its structure (large muscle with four chambers) and function (pumping blood) need to be understood (see Chi et al., 1991). However, the most important aspect is to consider how these aspects relate to each other, that is how the structure of the heart (being made of muscle and having four chambers) relates to its function of pumping blood. The results of Studies III and IV revealed that some medical students had problems understanding the relationship between anatomical and physiological aspects of the circulation system, resulting in so-called synthetic models. For example, in certain questions where the participants had to draw and explain blood flow in the human heart, the structures were correctly drawn, but the verbal explanation revealed that the fundamental idea that oxygen-poor and oxygen-rich blood do not mix in the heart was not understood.

This is an issue of concern because a single misconception about the structure or function of a system component or about a particular sequence of events can have repercussions for the conceptions of many other aspects (see Chi et al., 1991). Therefore, we wanted to investigate the relationship between the levels of biomedical understanding and clinical reasoning in Studies IV and V. Interestingly, our results show that those students who achieved the highest scores on the clinical reasoning task had remarkably increased their level of biomedical understanding of the CCVS during preclinical studies (Study IV). Further, the students who gave a correct diagnosis for the written patient case had slightly better results in biomedical and clinical tasks in previous years (Study V).

These findings should positively impact medical instruction by helping to make medical instructors more aware of the difficulty medical students may have regarding properly understanding biomedical content and the consequences that these challenges might present for clinical reasoning. Most medical educators are experts who have reorganised their own knowledge structures many times but who may no longer be aware of problems relating to the learning of basic biomedical knowledge. Further, the teaching of basic biomedical concepts should occur via active linking of anatomical and physiological aspects and highlighting causal relationships to facilitate systemic understanding. We argue that medical students should have the initial goal of mastering the most basic medical knowledge and that this should be a matter of concern in medical faculties. This would ensure understanding of the very basic biomedical topics before moving on to more complex content, such as clinical applications and diagnosis.

5.1.3 What does a reading process reveal about the diagnosing process of students and residents?

In Study V, medical students and residents read a written patient case about pulmonary embolus, the understanding of which requires knowledge about the CCVS. The eye movement data showed that those students who gave an incorrect diagnosis spent a significantly longer time processing the status and laboratory results of the patient case compared to those who gave a correct diagnosis. This perhaps indicates problems recognising the relevant aspects. Further, the literal answers of the students' showed that those students who gave a correct diagnosis named more relevant aspects from the case, whereas students who did not give a correct diagnosis named more irrelevant aspects. This result might support the assumption that the latter group of students had some difficulties distinguishing the 'noise' (e.g. irrelevant symptoms) from the substance (e.g. relevant symptoms), which led to the assumption that they focused on redundant aspects and at the same time ignored certain relevant aspects (see also Lesgold et al., 1988).

When comparing the student groups with the medical residents, the residents read all sentences except one remarkably faster compared to the students. It seemed that relative to other sentences, this particular sentence was processed more carefully by residents than by students. This deviating sentence was the very first key sentence of the case, which read: 'The patient is recuperating from a left knee surgery.' When analysing the eye-tracking data together with the complementary data from the written answer and the verbal explanations, it became evident that this particular sentence might have acted as an initiator of an illness script pattern for residents and possibly even for those students who diagnosed the case correctly. This result is somewhat in line with previous studies, in which it has been found that it is characteristic of medical experts to make better use of enabling conditions of specific cases compared to novices (e.g. Schmidt & Rikers, 2007).

Overall, experts' processing times were significantly shorter compared to those of students. Schmidt & Boshuizen (1993) have suggested that preclinical students' clinical processing is slower compared to experts because students have to activate the biomedical knowledge in a conscious fashion, a cognitive activity that takes considerable time because no ready-made structures are available. Our results support these findings. In addition, there was a clear difference between stronger and weaker students. The processing of stronger students to some extent resembled that of the residents. We suggest the students who performed worse might have been unable to recognise the pattern of the disease and consequently failed to provide the correct diagnosis (see also Monajemi, Schmidt & Rikers, 2012). The differences between student groups are interesting and need to be examined in more detail.

Based on the results, we suggest that medical students should become more aware of the crucial role of anamnesis. Anamnesis directs experienced doctors' reasoning process and may activate illness scripts (see also Boshuizen et al., 2012; Schmidt & Boshuizen, 1993). This enables effective and accurate decision making in a hectic hospital environment. Schmidt & Rikers (2007) suggest that to facilitate the development of expertise in medical school, it is important to teach the basic sciences in a clinical context and to introduce patient problems early in the curriculum to support the processes of encapsulation and illness script formation. We suggest that teaching 'illness script grammar' would help medical students to become aware of the illness script process and its different components, such as enabling factors and biomedical fault that explain how the enabling conditions can lead to consequences.

Overall, medical texts, such as epicrises, referrals, medical records and journal articles, are very complex documents with their own rules and structures (Charon, 2000). That is why research and instruction related to the reading of different medical texts would be beneficial. Medical education is highly valued and has been one of the leading actors in the development of university pedagogy. However, domain-specific pedagogy in medicine is still in its infancy.

5.2 Reflections on the quality of the studies

In this thesis, the multimethod approach was used in investigating science learning among medical and teacher education students. In the studies, different process methods, such as text interventions and eye tracking, was employed. We used a single case and group approaches, as well as longitudinal studies and cross-sectional samples. The multimethod and multilevel approach can be considered a strength of the current work. However, there are certain limitations related to the quality of the studies that need to be taken into account when considering generalising the results of the studies.

First, the low number of participants involved is a clear limitation, especially of Studies I and V. Both studies used a time consuming eye-tracking method in which the sample sizes are typically small because both the data collection and analysis are laborious. Another reason for small sample sizes is the in-depth perspective of this thesis. Learning researchers have published a substantial number of articles about different kinds of interventions that have successfully promoted conceptual change, but learning has typically been measured using different types of multiple-choice questionnaires that have been scored and used as an indication of conceptual change. Our purpose was to utilise a domain-specific perspective and an in-depth type of analysis as indicators of conceptual change. Therefore, in each sub-study, the analysis focused on both the case level and the group level. This perspective was laborious and time consuming for both the participants and the researchers and limited the sample sizes. However, we believe that the investment was worthwhile because open-ended questions with thorough qualitative and quantitative analysis methods provided us deeper, broader and more reliable information about the participants' learning processes. Furthermore, participation in each study was voluntary, which on one hand met the standards of good ethical practices but on the other hand resulted in challenges regarding the recruiting of participants.

To continue with the challenges related to the sample size, in Studies IV and V we faced some adversity, which seems to be common for all learning researchers carrying out complex longitudinal studies. In Study IV, we had three measurement points during two years and as many as five different measurement points during three years in Study V, the latter being a time-consuming eye-tracking study that lasted approximately 90 minutes and took place in students' free time. It is not surprising, therefore, that there were several drop-outs, as all participants were not able to take part in each study.

In addition, there were certain challenges deriving from the practical arrangements of the studies. One common problem in repeated measures studies is that the participants have to answer the same questions several times. In both Studies I and II, the participants answered the same, open-ended questions three times all together. Although in the posttest the participants could refer to their earlier answers, it raises questions about the motivational aspects and about the role of rote memory in the results. Concerning the factual questions, memory may play a role in the improvement in participants' answers, but when it comes to multifaceted and complex systemic questions, we assume that it is not possible to give high-level answers based on memory. In Study I, a delayed posttest was conducted seven months after the intervention. However, there were several drop-outs and the already small sample size decreased further. In Study II, we wanted to minimise the drop-out rate and conducted the delayed posttest just two weeks after the intervention, which is quite a short but realistic time period for such a multidisciplinary curriculum.

There were also some other limitations regarding the laboratory settings and the sample in Study V, where the participants read a patient case from a computer screen during which their eye movements were recorded. First, the experimental study design employed did not allow the participants to read the patient case as they perhaps normally would do, as the text was structured in a way that going back to previous slides was not possible. Second, it was not controlled whether some of the participants had more practical experience with the topic of the cases than others. In Study IV the level of clinical reasoning seemed to be related to increased biomedical understanding. Our purpose was to further examine in Study V certain cases from each groups of Study IV, but unfortunately this did not occur because only one participant from the group of the lowest performing student group participated in Study V. Therefore, we were not able to further investigate the causes that might explain the findings of Study IV.

Last, the conclusions drawn from the eye-tracking data and the complementary data relating to the results of illness-script initiation are based on the so-called eye–mind hypothesis, according to which the eye movements would indicate cognitive processing during the reading process. Kliegl, Nuthmann and Engbert (2006) presented an alternative view demonstrating that the mind might process several words in parallel at different perceptual and cognitive levels, the mind being ahead of the eyes at the fixation location (see also Rayner, 1977). Furthermore, complementing methods such as think-aloud protocols have been criticised because only conscious processes are able to be verbalised (Ericsson & Simon, 1993), leaving automated processes invisible. In addition, the participants may report their actions or thought processes in the way they believe the test leader wants (Hyrskykari et al., 2008). Finally, when interpreting the data of literal reports written after each slide, it must be taken into account that the literal questions may have acted as clues for what to focus on during reading of forthcoming text.

Studies III, IV and V indicated that there are several misconceptions about the CCVS among medical students. In longitudinal studies, biomedical understanding seemed to be centrally related to the level of clinical reasoning. However, in our studies, students' understanding of only one specific area of biomedical content was measured. The CCVS was chosen because it is a complex phenomenon in medicine for which a comprehensive understanding requires learning a great number of separate concepts and the ability to construct a flexible, simulation-like representation of the whole system. Furthermore, in this dissertation, the clinical reasoning was measured with only one task in Study IV and one patient case in Study V. In the future, it is essential to broaden the research with more evidence, to extend the study to include other biomedical systems and to investigate if these results can be generalised to other medical domains.

When considering the perspective and framing of this thesis on a larger scale, there are a few things that should be considered carefully. As mentioned in section 1.2, the concept of 'misconception' is somewhat problematic, although it is widely used across the studies in this thesis. The definition of the concept contains an assumption that there is some kind of mistake. This idea is problematic because of renewing nature of scientific knowledge. What we now call scientific knowledge may after a few years be dated or may even be found to be false. Further, because the learning of science phenomena is a gradual process, certain naïve conceptions can be considered as important 'transitional periods' towards a better scientific understanding. In addition, the definition of the concept is arguable because if one has no prior knowledge at all about a certain topic beforehand or if one has gaps in their knowledge, calling these things misconceptions is problematic. However, in this thesis, we have assumed that if, for example, a medical student does not mention lungs at all when explaining the circulatory system or if a teacher education student who has taken the compulsory biology courses does not include the role of the sun in their explanation of photosynthesis, these are considered misconceptions.

During the last decade, several learning researchers have been concerned that conceptual change has been taken on an over-rational approach (see e.g. Pintrich, Marx & Boyle, 1993). Posner and colleagues' original theory (1982) has been criticised for failing to consider the motivational aspects on learning. Today, several affective and motivational variables, such as intentional learning, are hypothesised to play an important role in conceptual change, and 'the warming trend' has become the focus of the conceptual change research tradition (see e.g. Cordova, Sinatra, Jones, Taasoobshirazi & Lombardi, 2014; Pintrich et al., 1993; Sinatra, 2005; Sinatra & Pintrich, 2003). These affective domains include emotions, goals, motivation and social aspects (see Duit et al., 2013). In their noteworthy article, Pintrich et al. (1993) suggested that students' goals, intentions, purposes, expectations and needs are as important as cognitive strategies in concept learning. Further, affective factors have an effect on students' studying, so that students who are interested in ruminating about complex problem solving tasks are more systematic in their studying compared to students who tend to avoid complex tasks (see Mäkinen & Olkinuora, 2004). This presumably may explain why among students with similar background knowledge, conceptual change may occur for some students but not for others (Sinatra, 2005). In this dissertation, the focus has been on cognitive aspects, and the warming trend was purposely not overly considered (Study I is an exception). However, the role of affective domains in learning is naturally important and undeniable. In future, these aspects must be taken into account more carefully to develop more effective science education.

5.3 Conclusions and future research directions

Although the medical and teacher education students are extremely select groups of talented and motivated students, they often begin their university studies holding serious misconceptions related to scientific phenomena central to their discipline. It is concerning that a number of misconceptions seem to remain even after instruction. These robust misconceptions may provide seemingly explanatory power, but they hinder the systemic learning of complex and multifaceted science phenomena and further prevent the higher level cognitive processing needed in problem solving tasks in varying circumstances. These results highlight the importance of advancing science instruction at each educational level from elementary school up to university. The research tradition of conceptual change provides a powerful framework for this.

However, as Duit et al. (2013) have stated, there is still a large gap between what is known in the research domain of conceptual change and what may be set into practice in normal science classrooms. In order to translate theoretical knowledge into good practices, a domain-specific perspective is needed because challenges to science learning are often fundamentally different for different domains and even sub-domains (see Treagust & Duit, 2008). The aim of this thesis was to contribute to domain-specific science instruction by examining the challenges related to learning about the key concepts of photosynthesis and the circulatory system at the university level. The results of this thesis provide detailed information about university students' conceptions of important biological content and concrete suggestions to support high-level science learning at the university level.

The aim of science education is for students to reach a level of understanding of scientific concepts that enables them to use those concepts as meaningful tools in various problem-solving situations in and outside the science classroom. This poses challenges for conceptualising certain complex and multifaceted concepts that may have different interpretations in scientific discussions compared to everyday contexts (see Wiser & Amin, 2001). Learning that a familiar word may have an unfamiliar meaning in a new context is likely to be problematic (Kinchin, 2000b). When studying photosynthesis, for example, this may include words as familiar as 'food' or 'energy' (Kinchin, 2000b), whereas in medical education, the principle of 'mass balance' is discussed very differently in different contexts (see Modell, 2000). Therefore, misconceptions may not simply be brought into classrooms as part of the naïve theories that have developed from everyday discourse and experience, but they may be present in the classroom itself in the language of teaching and can even be compounded by different patterns of use in different areas of the school curriculum (Kinchin, 2000b). Science teachers should therefore act as mediators between for example science language and everyday language to make potential misunderstandings clear to students.

Furthermore, because of the multifaceted nature of scientific concepts, a systemic approach needs to be taken when developing more effective science instruction at different educational levels. This means that although we do not deny the importance of learning details, 'usable knowledge' is not the same as a mere list of disconnected facts; rather, knowledge is organised around important concepts (Bransford et al., 2000). Systemic understanding enables science concepts to become dynamic tools that can be transferred (i.e. applied meaningfully) to various situations, for example, to make predictions and understand interrelations. Helping students to focus on interrelated concepts instead of unconnected facts in science classrooms will facilitate high-level learning of complex scientific phenomena. In addition, a systemic approach should be applied to the whole teaching and learning cycle in science classrooms, meaning that assessment methods and learning materials should facilitate systemic understanding and the usability of knowledge (for a review, see Mintzes, Wandersee & Novak, 2001).

Developing high-level learning materials is therefore essential in advancing science instruction in higher education. Learning materials that are developed based on previous research about the challenges of science learning, such as refutational texts that are specifically designed to facilitate the awakening of students' metaconceptual awareness, are needed. In future, digital learning materials, such as digital textbooks in combination with simulations, could have the potential to facilitate science learning at the university level, where a lot of independent studying of complex scientific topics is required. Thus far, however, new technological advantages such as computer simulations have often been reduced to step-by-step approaches in classrooms instead of tools to facilitate systemic understanding (Windschitl & Andre, 1998). The situation is similar with practical experiments that have lately been considered essential but are often being considered as self-evident support in science education, for experimental learning methods may support learning in science classrooms (see e.g. Kärnä, 2012), but only if they are linked to theory. For example, when dissecting a heart in a biology classroom, students must be clearly aware of which anatomical structures to focus on, what kind of functions different anatomical structures have and how the structure and functions of certain tissue are connected. Therefore, experiments and simulations do not benefit students per se, unless they do not fully understand what they are doing and why (see also Ross et al., 2005).

The challenge for both teacher education and medical education is that the curricula are already crowded and scientific knowledge is growing faster than ever before. It is therefore difficult even for science educators to keep up with the literature, not to mention the students who have to master very different topics in different disciplines. Therefore, university students need guidance regarding how to handle information overload. Furthermore, science instructors need to make sure that students master the material when it comes to the most essential key concepts. The risk that basic ideas of certain discipline deluge with less important knowledge is evident if students are not properly helped to conceptualise key ideas that form a foundation for understanding a certain discipline.

Although several suggestions are made here to advance science education, it must be noted that teaching and learning are multifaceted phenomena for which there is no fast track to learning. The process of conceptual change usually requires various changes of perspectives to open up a whole new conceptual space, and this usually takes time and effort (Duit, 2009; Treagust & Duit, 2008). Despite the fact that the literature has presented several teaching interventions to facilitate conceptual change (for a review, see Guzzetti et al., 1993), a single intervention does not usually lead to better learning outcomes. However, the learning environment needs to support conceptual change using various strategies to facilitate students' high-level learning (Duit et al., 2013). The designing of effective science learning environments therefore necessitates a solid domain-specific understanding and a deep understanding of the challenges associated with science learning in general. Science education would benefit from professional communities of experts with detailed knowledge of different domains to advance the teaching and learning of complex scientific phenomena.

Biology is discipline that investigates the features of life and living organisms, from the molecular level to the level of entire ecosystems. As the results of this dissertation have shown, the learning of biological content poses serious challenges, even for the most high-level student groups at the university level. Furthermore, because of the systemic nature of biological processes and phenomena, the misconceptions about central phenomena have wide-reaching consequences for the developing of expertise in medical and science education. The need to develop new materials and new teaching and learning practices in science classrooms is therefore critical to advance science understanding at the university level. This thesis has provided several suggestions regarding meeting this objective, but more research is still needed.

REFERENCES

Aivelo, T. & Uitto, A. (2015). Genetic determinism in the Finnish upper secondary school biology textbooks. *Nordic Studies in Science Education*, 11(2), 139–150.

Alvermann, D. E. & Hague, S. A. (1989). Comprehension of counterintuitive science text: effects of prior knowledge and text structure. *Journal of Educational Research*, 82, 197–202.

Ariasi, N. & Mason, L. (2011). Uncovering the effect of text structure in learning from a science text: An eye-tracking study. *Instructional Science*, 39 (5): 581–601.

Barak, J., Sheva, B. & Gorodetsky, M. (1999). As "process" as it can get: students' understanding of biological processes. *International Journal of Science Education*, 21 (12), 1281–1292.

Baumert, J., Kunter, M., Blum, W., Brunner, M., Voss, T., Jordan, A., Klusmann, U., Krauss, S., Neubrand, M. & Tsai, Y-M. (2010). Teachers' mathematical knowledge, cognitive activation in the classroom, and student progress. *American Educational Research Journal*, 47 (1), 133–180.

Boshuizen, H.P.A. & Schmidt, H.G. (1992). On the role of biomedical knowledge in clinical reasoning be experts, intermediates and novices. *Cognitive Science*, 16, 153–184.

Boshuizen, H.P.A., Schmidt, H.G., Custers, E. J .F .M. & Van de Wiel, M. W. (1995). Knowledge development and restructuring in the domain of medicine: the role of theory and practice. *Learning and Instruction*, 5, 269–289.

Boshuizen, H.P.A., van de Wiel, M., W., J. & Schmidt, H.G. (2012). What and how advanced medical students learn from reasoning through multiple cases. *Instructional Science*, 40, 755–768.

Braasch, J. L. G. Goldman, S. R. & Wiley, J. (2013). The influences of text and reader characteristics on learning from refutations in science texts. *Journal of Educational Psychology*, 105 (3), 561–578.

Bransford, J. D., Brown, A. L. & Cocking, R. R. (2000). *How people learn: Brain, Mind, Experience and School: Expanded Edition of Sciences*. Washington, D.C: National Academy Press.

Branstädter, K., Harms, U. & Groβschedl, J. (2012). Assessing System Thinking Through Different Concept-Mapping Practices. *International Journal of Science Education*, 34 (14), 2147–2170.

Broughton, S. E., Sinatra, G. M. & Reynolds, R. E. (2010). The nature of the refutation text effect: An investigation of attention allocation. *The Journal of Educational Research*, 103, 407–423.

Broughton, S. E., Sinatra, G. M. & Nussbaum E. M., (2013). "Pluto Has Been a Planet My Whole Life!" Emotions, Attitudes, and Conceptual Change in Elementary Students Learning about Pluto's Reclassification. *Research in Science Education*, 43 (2), 529–550.

Brown, M. H. & Schwartz, R. S. (2009). Connecting Photosynthesis and Cellular Respiration: Preservice Teachers' Conceptions. *Journal of Research in Science Teaching*, 46 (7), 791–812.

Campbell, N. A. & Reece, J. B. (2002). *Biology*. 6th Edition. Pearson Education, Inc., publishing as Benjamin Cummings. 1250 pp.

Carey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: MIT Press.

Chambliss, M. J. (2002). The characteristics of well-designed science textbooks. In J. Otero, J. Leön & A. C. Graesser (Eds.), *The psychology of science text comprehension* (pp. 51–72). Mahwah, NJ: Erlbaum.

Chambliss, M. J. & Calfee, R. C. (1998). *Textbooks for learning. Nurturing Children's minds*. Oxford, UK: Blackwell Publishers.

Chan, C., Burtis, J., & Bereiter, C. (1997). Knowledge building as a mediator of conflict in conceptual change. *Cognition and Instruction*, 15, 1–40.

Charlin, B., Boshuizen, H. P. A., Custers, E. J. & Feltovich, P. J. (2007). Scripts and clinical reasoning. *Medical Education*, 41, 1178–1184.

Charness, N., Reingold, E. M., Pomplun, M. & Stampe, D. M. (2001). The perceptual aspect of skilled performance in chess: Evidence from eye movements. *Memory & Cognition*, 29 (8), 1146–1152.

Charon, R. (2000). Reading, writing, and doctoring: Literature and medicine. *The American Journal of the Medical Sciences*, 319 (5), 285–291.

Chi, M. T. H. (1992). Conceptual change within and across ontological categories: examples from learning and discovery in science. In R. Giere (Ed.), *Cognitive models of science: Minnesota studies in the philosophy of science* (pp. 129–186). Minneapolis, MN: University of Minnesota Press.

Chi, M. T. H. (2005). Commonsense Conceptions of Emergent Processes: Why Some Misconceptions Are Robust. *The Journal of the Learning Sciences*, 14 (2), 161–199.

Chi, M. T. H. (2008). Three types of conceptual change: Belief revision, mental model transformation, and categorical shift. In. S. Vosniadou (Ed.), *International Handbook on conceptual change research* (pp. 61–82). New York: Routledge.

Chi, M. T. H. & Slotta, J. D. (1993). The Ontological Coherence of Intuitive Physics. *Cognition and Instruction*, 10, 249–260.

Chi, M. T. H. & Roscoe, R.D. (2002). The process and challenges of conceptual change. In: M. Limón & L. Mason (Eds.), *Reconsidering conceptual change. Issues in theory and practice* (3–27). Dordrecht, the Netherlands: Kluwer Academic Publishers.

Chi, M. T. H., Chiu, M-H. & deLeeuw, N. (1991). Learning in a Non-Physical Science Domain: The Human Circulatory System. Pittsburgh Univ., PA. Learning Research and Development Center.

Chinn, C. A. & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: a theoretical framework and implications for science instruction. *Review of Educational Research*, 63 (1), 1–49.

Clifton, C., Staub, A. & Rayner, K. (2007). Eye movements in reading words and sentences. In: R. P. G. van Gompel, M. H. Fischer, W. S. Murray & R. L. Hill (Eds.) *Eye movements: A window on mind and brain*. Oxford, UK: Elsevier Ltd.

Cordova, J. R., Sinatra, G. M. Jones, S. H., Taasoobshirazi, G. & Lombardi, D. (2014). Confidence in prior knowledge, self-efficacy, interest and prior knowledge: Influences on conceptual change. *Contemporary Educational Psychology,* 39, 164–174

Crane, L. & Winterbottom, M. (2008). Plants and photosynthesis: Peer assessment to help students learn. *Journal of Biological Education*, 42 (4), 150–156.

deBruin, A. B. H., Schmidt, H. G. & Rikers, R. M. J. P. (2005). The role of basic science knowledge and clinical knowledge in diagnostic reasoning: A structural equation modelling approach. *Academic Medicine*, 80 (8), 765–773.

Denis, A. U. Williams, J. J., Dunnamah, A. Y. & Tumba, D. P. (2015). Conceptual change theory as a teaching strategy in environmental education. *European Scientific Journal*, 11 (35), 395–408.

Diakidoy, I-A, N., Kendeou, P. & Ioannides, C. (2003). Reading about energy: The effects of text structure in science learning and conceptual change. *Contemporary Educational Psychology,* 28, 335–356.

Diakidoy, I-A, N., Mouskounti, T. & Ioannides, C. (2011). Comprehension and learning from refutation and expository texts. *Reading Research Quarterly*, 46 (1), 22–38.

diSessa, A. A. (1993). Toward an Epistemology of Physics. *Cognition and Instruction*, 10 (2/3), 105–225

diSessa, A. A. (2006). A history of conceptual change research: Threads and fault lines. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 265–281). Cambridge: Cambridge University Press.

Dole, J. A. & Sinatra, G. M. (1998). Reconceptualizing change in the cognitive construction of knowledge. *Education Psychologist*, 33, 109–128.

Donnon, T. & Violato, C. (2006). Medical Students' Clincal Reasoning Skills as a Function of Basic Science Achievement and Clinical Competency Measures: A Structural Equation Model. *Academic Medicine*, 81 (10), 120–123.

Donovan, M. S. & Bransford, J. D. (2005). *How students learn: history, mathematics and science in the classroom.* Washington, D. C: National Academic Press. 632 pp.

Driver, R. (1989). Students' conceptions and the learning of science. *International Journal of Science Education,* 11 (5), 481–490.

Duit, R. (2009). *Conceptual Change - Still a Powerful Framework for Improving the Practice of Science Instruction*. Keynote speech at the International Science Education Conference, Singapore. Accessed 12.2.2016.

Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education* 25, 6, 671-688.

Duit, R., Treagust, D. F. & Widodo, A. (2013). Teaching science for conceptual change – Theory and practice. In S. Vosniadou (Ed.): *International Handbook of Research in Conceptual Change.* Routledge, New York, NY.

Eilam, B. (2012). System thinking and feeding relations: learning with a live ecosystem model. *Instructional Science*, 40 (2), 213–239.

Ericsson, K. A. (2007). An expert-performance perspective of research on medical expertise: the study of clinical performance. *Medical Education*, 41, 1124–1130.

Ericsson, K.A. & Simon, H.A. (1993). *Protocol analysis: Verbal reports as data. Revised edition*. Cambridge, MA: The MIT Press.

Ericsson, K. A. & Kintsch, W. (1995). Long-Term Memory. *Psychological Review*, 102 (2), 211–245.

Evens, M., Elen, J. & Depaepe, F. (2015). Developing Pedagogical Content Knowledge: Lessons Learned from Intervention Studies. *Education Research International*, 1–23.

Feltovich, P.J. & Barrows, H.S. (1984). Issues of generality in medical problem solving. In *Tutorials in problem-based learning* (H. G. Schmidt & M. L. de Volder, Eds). Assen/Maastricht, The Netherlands, Van Gorcum 1984, 128–142.

Fyrenius, A., Silén, C. & Wirell, S. (2007). Students' conceptions of underlying principles in medical physiology: An interview study of medical students' understanding in a PBL curriculum. *Advances in Physiology Education*, 31, 364–369.

Gegenfurtner, A., Lehtinen, E. & Säljö, R. (2011). Expertise differences in the comprehension of visualizations: a meta–analysis of eye-tracking research in professional domain. *Educational Psychology Review*, 23, 523–552.

González, H. L., Palencia, A. P., Umaña, L. A., Galindo, L. & Villafrade M, L. A. (2008). Mediated learning experience and concept maps: a pedagogical tool for achieving meaningful learning in medical physiology students. *Advances in Physiology Education*, 32, 312–316.

Großschedl, J., Harms, U., Kleickmann, T. & Glowinski, I. (2015). Preservice biology teachers' professional knowledge: Structure and learning opportunities. *Journal of Science Teacher Education*, 26 (3), 291–318.

Guzzetti, B. J., Snyder, T. E., Glass, G. V. & Gamas, W. S. (1993). Promoting conceptual change in science: A comparative meta-analysis of instructional interventions from reading education and science education. *Reading Research Quarterly*, 28 (2), 116–159.

Guzzetti, B. J., Williams, W. O., Skeels, S. A. & Wu, S. M. (1997). Influence of text structure on learning counterintuitive physics concepts. *Journal of research in science teaching* 34, 701–719.

Haider, H. & Frensch, P.A. (1999). Eye movement during skill acquisition: more evidence for the information-reduction hypothesis. *Journal of Experimental Psychology: Learning, Memory and Cognition,* 25 (1), 172–190.

Hewson, P. W. (1982). A case study of conceptual change in special relativity: The influence of prior knowledge in learning. *European Journal of Science Education*, 4 (1), 61–78.

Hynd, C. R. (2001). Refutational texts and the change process. *International Journal of Educational Research* 35, 699–714.

Hynd, C. R. & Guzzetti, B. J. (1998). When knowledge contradicts intuition: Conceptual Change. In C. R. Hynd (Ed.) *Learning from Text across Conceptual Domains.* (pp. 139–163) Mahwah NJ: Lawrence Erlbaum Associates.

Hyrskykari, A., Ovaska, S., Majaranta, P., Räihä, K-J. & Lehtinen, M. (2008). Gaze path simulation in retrospective think-aloud. *Journal of eye movement research*, 2(4)5, 1–18.

Hyönä J. 2010. The use of eye movements in the study of multimedia learning. *Learning and Instruction*, 20, 172–176.

Inagaki K. & Hatano, G. (2013). Conceptual change in naïve biology. In: S. Vosniadou (Ed.). *International handbook of research on conceptual change: Second Edition* (pp. 195–219). New York: Routledge.

Jarodzka, H., Scheiter, K., Gerjets, P. & van Gog, T. (2010). In the eyes of the beholder: how experts and novices interpret dynamic stimuli. *Learning and Instruction*, 20, 146–154.

Johnson-Laird, P. N. (1983). *Mental models*. Cambridge, MA: Harvard University Press.

Just, M. A. & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review*, 87 (4), 329–354.

Kaufman, D. R., Keselman, A. & Patel, V. L. (2008). Changing conceptions in medicine and health. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 295–327). New York: Routledge.

Kendeou, P. & van den Broek, P. (2007). The effects of prior knowledge and text structure on comprehension processes during reading of scientific texts. *Memory & Cognition*, 35, 1567–1577.

Kinchin, I. M. (2000a). Concept mapping in biology. *Journal of Biological Education*, 34 (2). 61–68.

Kinchin, I. M. (2000b). Confronting problems presented by photosynthesis. *School Science Review*, 81(297), 69–75.

Kintsch, W. (1986). Learning from text. *Cognition and instruction*, 3 (2), 87–108.

Kintsch, W. (1988). The role of knowledge in discourse comprehension: A construction integration model. *Psychological Review*, 95, 163–182.

Kintsch, W. (1998). *Comprehension: A paradigm for cognition*. Cambridge: Cambridge University Press.

Kliegl, R., Nuthmann, A. & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology: General*, 135 (1), 12–35.

Kuhn, T. (1962). *The structure of scientific revolutions*. Chicago, IL: University of Chicago Press.

Kuijpers, J. M., Houtveen, A. A. M. & Wubbels, T. (2010). An intergrated professional development model for effective learning. *Teaching and Teacher Education*, 26, 1687–1694.

Kuipers, B. & Kassirer J. P. (1984). Causal reasoning in medicine: analysis of protocol. *Cognitive Science*, 8, 363–385.

Kundel, H. L., Nodine, C. F., Conant, E. F. & Weinstein, S. P. (2007). Holistic component of image perception in mammogram interpretation: Gaze-tracking study. *Radiology*, 242, 396–402.

Käpylä, Heikkinen & Asunta (2009). Influence of Content Knowledge on Pedagogical Content Knowledge: The case of teaching photosynthesis and plant growth. *International Journal of Science Education*, 31 (10), 1395–1415.

Kärnä, P., Hakonen, R. & Kuusela, J. (2012) Luonnontieteellinen osaaminen perusopetuksen 9. luokalla 2011. *Koulutuksen seurantaraportti 2*. Helsinki: Opetushallitus.

Lesgold, A. M., Rubinson, H., Feltovich, P. J., Glaser, R., Klopfer, D & Wang, Y. (1988). Expertise in a complex skill: Diagnosing x-ray pictures. In M. T. H. Chi, R. Glaser & M. Farr (Eds.). T*he nature of expertise* (pp. 311–342. Hillsdale, NJ: Erlbaum.

Limón, M. (2001). On the cognitive conflict as an instructional strategy for conceptual change: a critical appraisal. *Learning and Instruction*, 11, 357–380.

Limón, M. & Mason, L. (2002). Prologue. In M. Limón & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. xv–xx). Dordrecht, NL: Kluwer Academic.

Lombardi, D., Sinatra, G. M. & Nussbaum, E. (2013). Plausibility reappraisals and shifts in middle school students' climate change conceptions. *Learning and Instruction*, 27, 50–62.

Mann, D. T. Y., Williams, A. M. & Ward, P. & Janelle, C. M. (2007). Perceptual-Cognitive Expertise in Sport: A Meta-Analysis. *Journal of Sport & Exercise Psychology*, 29, 457–478.

Maria, K. (2000). Conceptual change instruction: A social constructivist perspective. *Reading and writing quarterly*, 16, 5–22.

Mason, L. (2001). Responses to anomalous data and theory change. *Learning and Instruction*, 11 (6), 453–483.

Mason, L., Gava, M. & Boldrin, A. (2008). On warm conceptual change: The interplay of text, epistemological beliefs, and topic interest. *Journal of Educational Psychology*, 100 (2), 291–309.

Mayr, E. (1997). *This is biology: The science of the living world*. Cambridge, MA: Belknap Press.

Michael, J. A., Modell, H., McFarland, J. & Cliff, W. (2009). The "core principles" of physiology: what should students understand? *Advances in Physiology Education*, 33, 10–16.

Michael, J. A., Richardson, D., Rovick, A., Modell, H., Bruce, D., Horwitz, B., Hudson, M., Silverthorn, D., Whitescarver, S. & Williams, S. (1999). Undergraduate students' misconceptions about respiratory physiology. *Advances in Physiology Education*, 277, 127–135.

Michael, J. A., Wenderoth, M. P., Modell, H. I., Cliff, W., Horwitz, B., McHale, P., Richardson, D., Silverthorn, D., Williams, S. & Whitescarver, S. (2002). Undergraduates' understanding of cardiovascular phenomena. *Advances in Physiology Education*, 26, 72–84.

Mikkilä-Erdmann, M. (2001). Improving conceptual change concerning photosynthesis through text design. *Learning and Instruction*, 11, 241–257.

Mikkilä-Erdmann, M. (2002). Text comprehension and conceptual change: Interaction between text design and levels of text comprehension. In: L. Mason and M. Limon (eds.) *Reframing the processes of conceptual change: Integrating theory and practice* (s. 337–356). Netherlands: Kluwer Academic Publishers.

Mikkilä-Erdmann, M., Penttinen, M., Anto, E. & Olkinuora, E. (2008). Constructing mental models during learning from science text. In D. Ifenthalter, O. Pirnay-Dummer & J. M. Spector (Eds.), *Understanding models for learning and instruction*. Essays in honor of Norbert M. Seel (pp. 63–79). New York: Springer.

Mintzes, J. J. & Wandersee, J. H. (2005). Research in science teaching and learning: A human constructivist view. In: J. J. Mintzes, J. H. Wandersee & J. D. Novak (Eds.), *Teaching science* *for understanding: A human constructivist view* (s. 59–92). San Diego, CA: Academic Press.

Mintzes, J. J., Wandersee, J. H. & Novak, J. D. (2001). Assessing understanding in biology. *Journal of Biological Education*, 35 (3), 118–124.

Modell, H. I. (2000). How to help students understand physiology? Emphasize general models. *Advances in physiology education*, 23 (1), 101–107.

Monajemi, A., Schmidt, H. G. & Rikers, R. M. J. (2012). Assessing patient management plans of doctors and medical students: an illness script perspective. *Journal of continuing education in the health professions*, 32 (1), 4–9.

Mäkinen, J. & Olkinuora, E. (2004). University Students' Situational Reaction Tendencies: reflections on general study orientations, learning strategies, and study success. *Scandinavian Journal of Educational Research*, 48 (5), 477–491.

Nesbit, J C. & Adesope, O. O. (2006). Learning with concept and knowledge maps: A meta-analysis. *Review of Educational Research*, 76 (3), 413–448.

Nodine, C. F., Mello-Thoms, C., Kundel, H. R. & Weinstein, S. P. (2002). Time course of perception and decision making during mammographic interpretation. *American Journal of Roentgenology*, 179, 917–923.

Novak, J. D. & Cañas, A. J. (2006). The origins of the concept mapping tool and the continuing evolution of the tool. *Information Visualization Journal*, 5 (3), 175–184.

Papadimitriou, V. (2004). Prospective Primary Teachers' Understanding of Climate Change, Greenhouse Effect, and Ozone Layer Depletion. *Journal of Science Education and Technology*, 13 (2), 299–307.

Patel, V. L., Evans, D. A. & Groen, G. J. (1989). Biomedical knowledge and clinical reasoning. In D. A. Evans & V. L. Patel (Eds.), *Cognitive science in medicine: Biomedical modelling* (pp. 53–112). Cambridge, MA: The MIT Press.

Patel, V. L., Evans, D.A & Kaufman, D. R. (1990). Reasoning strategies and the use of biomedical knowledge by medical students. *Medical Education*, 24, 129–136.

Penttinen, M., Anto, E. & Mikkilä-Erdmann, M. (2013). Conceptual change, text comprehension, and eye movements during reading. *Research in Science Education*, 43, 1407–1434.

Piaget, J. (1970). *Structuralism*. New York, NY: Basic Books.

Pintrich, P. R., Marx, R. W. & Boyle, R. A. (1993). Beyond cold conceptual change: the role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research*, 63 (2), 167–199.

Plate, R. (2010). Assessing individuals' understanding of nonlinear causal structures in complex systems. *System Dynamics Review*, 26 (1), 19–33.

Posner, G. J. Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, 66, 211-227.

Ratinen, I. J. (2013). Primary Student-teachers' conceptual understanding of the greenhouse effect: a mixed method study. *International Journal of Science Education*, 35 (6), 929–955.

Ratinen, I., Viiri, J. & Lehesvuori, S. (2013). Primary school student teachers' understanding of climate change: Comparing the results given by concept maps and communication analysis. *Research in Science Education*, 43 (5), 1801–1823.

Rayner, K. (1977). Visual attention in reading: Eye movements reflect cognitive processes. *Memory & Cognition*, 5 (4), 443–448.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years research. *Psychological Bulletin*, 124 (3), 372–422.

Rayner, K. (2009). Eye Movements in Reading: Models and Data. *Journal of Eye Movement Research,* 2 (5): 2, 1–10.

Ross, P., Tronson, D., & Ritchie, R.J. (2005). Modelling photosynthesis to increase conceptual understanding. *Journal of Biological Education,* 40, 84–88.

Roth, K. (1990). Developing meaningful conceptual understanding in science. In: B. Jones & L. Idol (Eds.), *Dimensions of thinking and cognitive instruction* (s. 139–175). Hillsdale; NJ: Lawrence Erlbaum Associates.

Schmidt, H.G. & Boshuizen, H.P.A. (1993). On acquiring expertise in medicine. *Educational Psychology Review*, 5 (3), 205–221.

Schmidt, H. G. & Rikers, R. M. J. P. (2007). How expertise develops in medicine: knowledge encapsulation and illness script formation. *Medical Education*, 41, 1133–1139.

Schulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review*, 57, 1–22.

Scott, P., Dyson, T. & Gater, S. (1987). *A constructivist view of learning and teaching in science*. Leeds: University of Leeds.

Sinatra, G. M. (2005). The "warming trend" in conceptual change research: The legacy of Paul R. Pintrich. *Educational Psychologist*, 40 (2), 107–115.

Sinatra, G. & Mason, L. (2013). Beyond knowledge: Learner characteristics influencing conceptual change. In: S. Vosniadou (Ed.), *International handbook on conceptual change research: second edition* (pp. 377–394). New York: Routledge.

Sinatra, G. M. & Pintrich, P. R. (2003). *Intentional Conceptual Change*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Södervik, I., Mikkilä-Erdmann, M. & Vilppu, H. (2014). Promoting the Understanding of Photosynthesis among Elementary School Student Teachers through Text Design. *Journal of Science Teacher Education*, 25, 581–600.

Tippett, C. D. (2010). Refutation text in science education: a review of two decades of research. *International Journal of Science and Mathematics Education*, 8, 951–970.

Treagust, D.T. & Duit, R. (2008). Conceptual change: a discussion of theoretical, methodological and practical challenges for science education. *Cultural Studies of Science Education,* 3, 297–328.

Tullberg, A., Strödahl, H. & Lybeck, L. (1994). Students' conceptions of 1 mole and educators' conceptions of how they teach "the mole". *International Journal of Science Education*, 16, 145–156.

Uitto, A. (2012) Näkökulmia biologian opettamisen kehittämiseksi. In: P. Kärnä, L. Houtsonen & T. Tähkä (Eds.) *Luonnontieteiden opetuksen kehittämishaasteita. Koulutuksen seurantaraportti 10*. Helsinki: Opetushallitus.

Van de Wiel, M. W. J., Boshuizen, H. P. A. & Schmidt, H. G. (2000). Knowledge restructuring in expertise development: Evidence from pathophysiological representations of clinical cases by students and physicians. *European Journal of Cognitive Psychology*, 12 (3), 323–355.

Verhoeff, R. P., Waarlo, A. J. & Boersma, K. T. (2008). Systems modeling and the development of coherent understanding of cell biology. *International Journal Science Education*, 30, 543–568.

Vilppu, H. (2016). *University Students' Regulation of Learning and Text Processing- Examples from Medical and Teacher Education*. Annales Universitatis Turkuensis, ser. B, tom. 415. Turku, Finland: Painosalama.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction* 4, 45–69.

Vosniadou, S. (2008). Conceptual Change Research: an Introduction. In: S. Vosniadou (Ed.), *International handbook on conceptual change research* (pp. xiii–xxviii). New York: Routledge

Vosniadou, S. (2013). Conceptual change in learning and instruction – The Framework Theory Approach. In: S. Vosniadou (Ed.), *International handbook on conceptual change research: second edition* (pp. 11–30). New York: Routledge.

Vosniadou, S. & Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology*, 24, 535–585.

Vosniadou, S., Ioannides, C., Dimitrakopoulou, A. & Papademetriou, E. (2001). Designing learning environments to promote conceptual change in science. *Learning and Instruction*, 11, 381–419.

Vosniadou & Ioannides (1998). From conceptual development to science education: A psychological point of view. *International Journal of Science Education*, 20, 1213–1230.

Vosniadou, S. & Skopeliti, I. (2005). Developmental shifts in children's categorization of the earth. In B. G. Bara, L. Barsalou & M. Bucciarelli (Eds.), *Proceedings of the XXVII Annual Conference of the Cognitive Science Society* (pp. 2325–2330) Mahwah, NJ: Lawrence Erlbaum Associates.

Vosniadou, S., Vamvakoussi, X. & Skopeliti, I. (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.). *International handbook of research on conceptual change* (pp. 3–34). New York: Routledge.

Vygotsky, L. S. (1994). The development of academic concepts in school aged children. (Original in 1934). In R. Van der Veer & J. Valsiner (Eds.). *The Vygotsky Reader* (pp. 355–370). Oxford: Blackwell.

Wadouh, J., Liu, N., Sandmann, A. & Neuhaus, B. (2014). The effect of Knowledge Linking Levels in Biology Lessons upon Students' Knowledge Structure. *International Journal of Science and Matematics Education*, 12 (1), 25–47.

Wandersee, J. H., Mintzes, J. J. & Novak, J. D. (1994). Research on Alternative Conceptions in Science. In: D. L. Gabel (Ed.). *Handbook of research on science teaching and learning* (pp. 177–210). New York: Simon & Schuster Macmillan.

Wellington, J. & Osborne, J. (2009). *Language and literacy in science education*. Glasgow, UK: Open University Press.

Wilhelmsson, N. (2010). *From Basic science knowledge to clinical understanding*. Stockholm, Karolinska Institutet: Larserics Digital Print AB.

Windschitl, M. & Andre, T. (1998). Using computer simulations to enhance conceptual change: the roles of constructivist instruction and student epistemological beliefs. *Journal of research in science teaching*, 35 (2), 145–160.

Wiser, M. & Amin, T. (2001). "Is heat hot?" Inducing conceptual change by integrating everyday and scientific perspectives on thermal phenomena. *Learning and Instruction*, 11, 331–355.

Woods, N. N. (2007). Science is fundamental: The role of biomedical knowledge in clinical reasoning. *Medical Education*, 41, 1173–1177.