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NANOSCIENCE EDUCATION FOR SCIENTIFIC LITERACY
OPPORTUNITIES AND CHALLENGES IN SECONDARY SCHOOL
AND IN OUT-OF-SCHOOL SETTINGS

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ACADEMIC DISSERTATION

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ABSTRACT

The rapid development and growing societal importance of nanoscience and nanotechnology (NST) have evoked educational concerns throughout the world. A mounting need for education in this emerging field has been **recognized not only at the academic level but also in terms of citizens' abilities to deal with personal, social and global issues related to NST**. Some understanding of NST has been postulated to be relevant in up-to-date scientific literacy for all.

This doctoral dissertation addresses such concerns and lays the research-based groundwork for the future development of learning environments on NST. The aim was to map the educational needs, possibilities and challenges of bringing the topics of NST to secondary schools and out-of-school settings. To this end, the methodological framework of the Model of Educational Reconstruction was employed. The model combines analytical and empirical research in order to analyse **a field's educational significance, identify its essential features, investigate both learners' and teachers' perspectives and develop approaches for teaching and learning**. Accordingly, the research presented here adopted a pragmatist multi-method approach to scrutinize NST from diverse educational viewpoints.

The role of NST in scientific literacy was first explored through a theoretical-analytical study on the content structure, the nature and the implications of NST. Next, a group of secondary school teachers who had attended a course on NST was invited to evaluate the educational significance **of the field's contents and their appropriateness for the curriculum**. Another **survey addressed Finnish science teachers' views on barriers that hinder incorporating NST into the curriculum, and facilitators for overcoming these barriers**. Specific challenges in learning and communicating NST were investigated through a literature review that was subsequently complemented with an interview study on science **centre visitors'** perspectives on NST. On the basis of all these findings, research-based suggestions were put forth for the planning of NST education both in classrooms and through visits to science exhibitions and industry sites.

Both theoretical and empirical analyses identified several content areas as well as social and epistemological aspects of NST that render the field educationally interesting and relevant to scientific literacy. The results imply that, by addressing NST, science education could stimulate dialogue on important contemporary issues in the intersection of science, technology and society, and provide up-to-date views on the nature of science. However, the teachers also pointed out a number of difficulties in arranging instruction on NST in practice. Many of the indicated barriers are extrinsic to teachers and related to curricular constraints in particular. It is concluded that NST would be best incorporated in the curriculum as a transdisciplinary theme. The field

has, in addition, a potential to integrate traditional science subjects and approaches by shifting the focus to the scale of natural phenomena. In any case, including NST in science classes also requires in-service teacher training and new resources for materials and equipment.

This dissertation highlights the research outcomes that should be taken into account when planning any learning environments on NST. Prior research has identified several challenges in learning and communicating NST, but also effective strategies for supporting the understanding of the nanoscale and its phenomena. The results of the interview study carried out here confirmed earlier findings. For instance, they implied that scanning tunnelling microscope (STM) images, powerful and thus used extensively in nanoscience communication, are liable to cause epistemological misunderstandings.

Some of the identified barriers for teaching NST may be circumvented by out-of-school methods. This dissertation suggests research-based models for the development of two specific learning environments: exhibitions in science museums and school group visits to industrial sites. The models strive to bridge the notorious gap between academic research and the development of educational practice. Their application to NST education as well as their broader implications are discussed. Furthermore, some methodological issues are raised because this research also explored the potential of the Model of Educational Reconstruction in informal and out-of-school contexts.

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Research publications **I–V**, introduced on the following page, are included as appendices in the printed version of this dissertation. They are reprinted by permission of the publishers.

LIST OF PUBLICATIONS

This thesis is based on the following publications, which are referred to in the text by their Roman numerals **I–V**.

- I** Laherto, A. (2010). An analysis of the educational significance of nanoscience and nanotechnology in scientific and technological literacy. *Science Education International*, *21*(3), 160–175.
- II** Laherto, A. (2011). Incorporating nanoscale science and technology into secondary school curriculum: Views of nano-trained science teachers. *NorDiNa - Nordic Studies in Science Education*, *7*(2), 126–139.
- III** Kähkönen, A., Laherto, A., & Lindell, A. (2011). Intrinsic and extrinsic barriers to teaching nanoscale science: Finnish teachers' perspectives. *Journal of Nano Education*, *3*(1), 1–12.
- IV** Laherto, A. (2012). Informing the development of science exhibitions through educational research. Accepted for publication in *International Journal of Science Education, Part B: Communication and Public Engagement*. DOI: 10.1080 / 21548455.2012.694490
- V** Lavonen, J., Laherto, A., Loukomies, A., Juuti, K., Kim, M., Lampiselkä, J., & Meisalo, V. (2009). Enhancing Scientific Literacy through the Industry Site Visit. In S. Rodrigues (Ed.), *Multiple Literacy and Science Education: ICTs in Formal and Informal Learning Environments* (pp. 225–239). Hershey, PA: Information Science Reference.

The author's contributions to the publications:

I, II and **IV**: The author alone was responsible for planning and setting up the research, collecting and analysing the data, drawing conclusions and writing all parts of the article.

III: The author was responsible for planning and writing the theoretical framework of the article. The author also participated in designing the questionnaire, drawing conclusions from the data, and writing all parts of the article.

V: The author was responsible for planning and writing the theoretical framework of *scientific literacy* and connecting the study to this frame. The author also participated in writing the other parts of the article.

1 INTRODUCTION

During the past decade, nanoscience and nanotechnology (NST) have become major fields of scientific research and technological innovation. Their growing socio-economic potential has attracted substantial investments from both the public and private sectors. Nanotechnological products have started to invade the markets. At the same time, the prospects of more significant applications and implications of NST have aroused active socio-scientific debate on various societal and global issues and ethical concerns.

Due to this development, NST has also become an interesting and important field from educational perspectives. Calls for nanoscience education have been made not only with regard to the academic level: several bodies have argued that the contents of NST should already be taught in **compulsory education, and the general public's awareness of and engagement** in these emerging fields should be promoted. Such demands have been made by public administrations, industry and commerce, civic organizations, scientists and engineers, teachers and educationalists, and social scientists. The demands have been motivated in a variety of ways. Firstly, a critical shortage in the NST-educated workforce has been forecasted, e.g., by the OECD¹ (Palmberg, Dernis, & Miguet, 2009) and the European Commission (2005; 2010). Another key argument is the need to **support citizens' abilities to deal with NST-related issues** within the personal, social and global contexts. Since it is likely that all citizens will increasingly confront such issues in the near future, some understanding of NST has become relevant in up-to-date *scientific literacy* (e.g. Gardner, Jones, Taylor, Forrester, & Robertson, 2010; Healy, 2009; Sabelli et al., 2005; Stevens, Sutherland, & Krajcik, 2009; Zenner & Crone, 2008).

These demands have been answered throughout the world to some extent. Besides increasing NST education at the academic level², several initiatives have recently explored the possibilities to bring these topics to secondary schools³ as well as informal learning environments⁴. Systematic and wide-ranging efforts to identify the educationally central contents of NST have been made in the U.S. (Sabelli et al. 2005; Stevens et al. 2009; Wansom et al. 2009), and novel approaches and modules for NST teaching are frequently reported in the international literature on science and engineering education

1 The Organisation for Economic Co-operation and Development.

2 For comprehensive reviews, see Baraton, Monk, & Tomellini (2008) and Brune et al. (2006).

3 For multiple examples, see Murday (2009) and Sweeney & Seal (2008). In the EU, classroom activities have been developed within the NANOYOU project (<http://nanoyou.eu/>).

4 For European examples, see Gyalog (2007) and the EU projects NANOTOTOUCH (<http://www.nanototouch.eu/>), NANOYOU (<http://nanoyou.eu/>) and Time for Nano (<http://www.timefornano.eu/>). For U.S. examples, visit the Nanoscale Informal Science Education network (<http://www.nisenet.org/>).

(e.g. Jones, Andre, Superfine, & Taylor, 2003; Stevens, Delgado, & Krajcik, 2010; Sweeney & Seal, 2008). American Scientific Publishers has even launched a new peer-reviewed journal⁵ dedicated to such papers. Despite this growing interest in the field of NST among the science education research community, a recent review article (Hingant & Albe, 2010) has revealed a need for additional, in-depth research on the related educational issues.

The research presented in this dissertation responded to these demands by carrying out a set of analytical and empirical studies in order to map the educationally significant aspects of NST in terms of scientific literacy, and the possibilities and challenges of bringing NST to schools and out-of-school learning environments. The studies employed a variety of research methods and approaches. The common methodological framework was the Model of Educational Reconstruction (Duit, Gropengieser, & Kattman, 2005).

The first article of this dissertation employed a theoretical-analytical approach to scrutinize the educational significance of nanoscience and nanotechnology with regard to scientific and technological literacy (**I**). The following two articles report empirical investigations on related issues, both **surveying science teachers' views**. The second article focuses on the general need, contents and resources for NST education (**II**), while the third article more closely examines **teachers' perceptions of barriers that hinder** the incorporation of NST into the curriculum, and facilitators for overcoming these barriers (**III**). The last two articles discuss the opportunities for NST education offered by out-of-school learning environments. The fourth article deals with the development of exhibitions in museums and science centres. It generally calls for greater use of educational research in exhibition development, and specifically suggests how such research can be incorporated into the planning of an NST exhibition (**IV**). The last article introduces a model for organising industry site visits and discusses their potential when connected to other learning activities in lower secondary school science education (**V**). Such visits provide a feasible way for introducing NST to students. Together, the studies reported in these five articles lay the groundwork for the development of teaching and learning of NST in schools and outside of them.

The following chapter introduces the theoretical background of the dissertation, covering the main rationales and aspects of NST teaching and learning in various educational settings. Chapter 3 introduces the research problem, research questions and the chosen strategy for answering them, i.e. the methodological framework of the Model of Educational Reconstruction. After that, Chapter 4 breaks down the methods of the various partial studies of the multi-method approach. Chapter 5 presents the results, while the validity and reliability of the whole study is considered in Chapter 6. The concluding Chapter 7 summarises the answers to the research questions and discusses the implications.

⁵ The Journal of Nano Education (<http://www.aspbs.com/jne.htm>).

2 BACKGROUND: RATIONALES AND SETTINGS FOR NANOSCIENCE EDUCATION

2.1 NANOSCIENCE AND NANOTECHNOLOGY (NST)

Nanoscience and nanotechnology are developing rapidly, and notable technological, economic and societal prospects are attached to these fields. With increasing promises and general attention, there has been an explosion of both public and private funding and investments in NST. The OECD forecasts employment relating to NST to increase by 2 million positions worldwide by 2015 (Palmberg, Dernis, & Miguet, 2009). In the same report, the total market value of nanotechnology products is estimated to top one thousand billion U.S. dollars. The prospects of nanotechnology involve both benefits and risks concerning the environment, safety and health (Gardner et al., 2010; Hunt & Mehta, 2006; Schwarz, 2004; Moor & Weckert, 2004; Berne, 2008). Meanwhile, the visions of nanotechnology have also been **doubted and challenged by the critics of “nanohype” (see e.g. Mitchell, 2007).**

Despite the growing attention on these fields, the concepts of nanoscience and nanotechnology have remained ambiguous and without a universally accepted definition. The literature on the nature of NST (e.g. Baird, Nordmann, & Schummer, 2004; Brune et al., 2006; Cameron & Mitchell, 2007; Hunt & Mehta, 2006), and textbooks and overviews on NST (e.g. Nalwa, 2004; Poole & Owens, 2003) show that the field is a complex and disordered conglomeration of various questions, methods, technologies and findings. Commonly, the nanometre scale of objects (together with the purposeful control of matter at that scale, and some aspect of novelty either in methods, findings or applications) serves as a justification for considering a field as *nanoscience* or *nanotechnology*. The scale is the main defining factor in the most influential definitions of NST, e.g. the relatively inclusive ones presented by the European Union and the U.S. National Nanotechnology Initiative (for a collection and comparison of other definitions, see Palmberg, Dernis, & Miguet, 2009):

Nanosciences and nanotechnologies are new approaches to research and development that concern the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a large scale.

European Commission, 2005

Nanotechnology is the ability to understand, control and manipulate matter at the level of individual atoms and molecules, as well as the

‘supramolecular’ level involving clusters of molecules (in the range of about 0.1 to 100 nm), in order to create materials, devices, and systems with fundamentally new properties and functions because of their small structure.

Roco, 2007

Highlighting the size scale as the common nominator in NST is also typical when discussing the interdisciplinarity of the fields in question. Considerable expectations rest on the notion that NST interlinks many traditional fields of research in physics, chemistry, biology, material science, medicine, computer science and engineering (see e.g. Brune et al., 2006; Stevens et al., 2009). A common argument is also that it is specifically the multi/interdisciplinary approach that makes NST new (see e.g. Sabelli et al., 2005). In any case, interdisciplinarity – collaboration between researchers from different fields – must generally be based on some common ground other than disciplinary knowledge. In NST, this common ground is mostly the size scale of objects (cf. Schummer, 2004). Research is focused on the scale, the ‘nanoworld’, rather than some problems that are specific to a certain discipline. Nordmann (2004) even argues that NST is a fundamentally place-oriented enterprise that primarily seeks to settle and stake claims at the nanoscale, instead of the commonly stated ‘official’ goals such as understanding nature, or the production of devices and substances. However, Schummer (2004) questions the sufficiency of a shared scale in integrating various disciplinary perspectives because of the fundamentally different research approaches, e.g. the ideas of atom-by-atom manipulation and self-assembly.

Brune et al. (2006) also argue that typical definitions of nanoscience, based on the size of the objects, present some epistemic problems. Thus, they suggest that the demarcation should be made through new phenomena hitherto unknown in familiar domains, and propose the following definition:

Nanotechnology comprises the emerging applications of Nanoscience. Nanoscience is dealing with functional systems either based on the use of sub-units with specific size-dependent properties or of individual or combined functionalized subunits.

Brune et al., 2006

The properties in question cover magnetic, mechanic, electronic, optical, thermodynamic and thermal features as well as the abilities for self-assembly and recognition. These properties are size-dependent and have no equivalent in the macroscopic world when they:

- no longer follow classical physical laws but rather are described by quantum mechanical ones;*
- are dominated by particular interface effects;*

- exhibit properties due to a limited number of constituents, since the usual term 'material' refers to an almost infinite number of constituents (e.g. atoms, molecules) displaying an averaged statistical behavior.

Brune et al., 2006

This definition is somewhat narrower than the majority of suggested definitions. The main distinguishing feature is that Brune et al. focus solely on new functions and properties as the essence of nanotechnology, while leaving the size only as a coincidental or instrumental property at best. In fact, according to this definition, not all the effects within the interval between 0.1 nm and 100 nm count as nanotechnology, while on the other hand, some effects can occur well above 100 nm and still show these *specific size-dependent properties*. Above all, left out of this definition are *the scaling effects*, where macroscopic laws are simply transformed to small scales by miniaturization without coming to a significant change of properties at a distinct dimension, although they are commonly designated as nanotechnology⁶.

With respect to material science, the roots of nanoscience lie in grain refinement, which has proved to be a powerful tool in improving the properties of materials, and has thereby been an important field for several decades. The research and development of nanostructured materials emerged as a continuation of this in the late 1980s (Brune et al. 2006). An understanding of size-dependent properties is a prerequisite for generating physical or chemical 'nanoeffects' and transferring them into practical applications. Thus, basic research on nanomaterials is arguably a cornerstone of nanoscience and nanotechnologies. The development of high-strength materials and composites has been one of the focal points of nanotechnology related to material physics. Nanoscale materials science also encompasses a number of engineered functions of complex nanomaterials, including hybrids, composites, boundary surfaces, molecules and assemblies (Poole & Owens, 2003; Nalwa, 2004).

Nanoscience has led us to a new understanding of material-specific properties. The electronic structure of a nanoparticle in the size range between a molecule and a macroscopic solid is something in between the discrete energy levels of an atom or molecule and the band structure of bulk material. Consequently, in this intermediate state, matter shows new physical properties originating from the quantization of electronic states. This size-dependent change in material properties is usually referred to as the *quantum size effect* (Poole & Owens, 2003, p. 82).

Current fields in which nanoscale effects are applied have been reviewed, for example, by Brune et al. (2006), Nalwa (2004), and Poole and Owens

⁶ Such fields based on scaling effects **include several successful 'nanotechnologies'**, e.g. field emission displays and nanostructured surfaces for various practical purposes.

(2003). Here, only a few examples of thriving areas of nanoengineering are presented. To begin with, new information storage systems utilizing size-dependent nanoscale effects are of enormous importance. Multiple information storage technologies are currently under development (based on spintronics, for example), and many of them seem to be plausible candidates for replacing the current CMOS technology in the future (Brune et al., 2006). Nanotechnology is also considered to offer enormous biomedical prospects. Due to the extent of conceivable societal implications, the public and political interest in biomedical nanotechnology is wide (Cameron & Mitchell, 2007). Furthermore, it is commonly acknowledged that nanomaterials can be employed in favour of the environment. These benefits are expected to arise, for instance, from the development of novel types of pollutant filters and more efficient energy production and storage technologies (see e.g. Cameron & Mitchell, 2007; Roco & Bainbridge, 2005). On the other hand, the main risk of nanomaterials concerns the lack of knowledge concerning the health and environmental impacts of releasing nanoparticles into the environment (Glimell, 2004; Hunt & Mehta, 2006; Roberts, 2004).

These emerging fields have also been of particular interest to many philosophers of science. Due to the novelty of NST, a well-established philosophy of the field does not yet exist: the volume and consistency of publications are still low compared to the philosophical literature on the mature disciplines. However, some scholarly writings have already been published, and several philosophically interesting aspects of nanoscience have been pointed out (e.g. Cameron & Mitchell, 2007; Lenhard, 2004; Moor & Weckert, 2004; Nordmann, 2004; Pitt, 2004). Based on philosophical analysis, some scholars have even suggested that nanoscience and nanotechnology should be seen as an epistemic revolution or a paradigm change (Khushf 2004, Schmidt 2004). In any case, philosophical considerations of these fields give rise to many issues of educational relevance, as discussed later in this dissertation.

2.2 SCIENTIFIC LITERACY

Enhancing *scientific literacy* (SL) is a major educational objective worldwide. The concept has developed into an umbrella term covering virtually everything regarding science education (see e.g. Laugksch, 2000; Shamos, 1995). This ambiguity stems from the diversity of underlying reasons for promoting SL, including various standpoints and benefits at both the personal and social as well as the national and global levels (Fensham, 2002; McEneaney, 2003; Sjøberg, 1997). Many scientists and technologists, for example, see the promotion of SL chiefly as a means to ***strengthen the public and political support for science and technology*** (Laugksch, 2000; Shamos, 1995). Researchers generally assume that more scientifically and technologically literate citizens – and politicians – are more apt to support

public expenditure on science and technology enterprises. Another commonly stated reason for enhancing SL, closely related to the one just mentioned, is the need to ***ensure a steady supply of scientists, engineers and science-related professionals*** (cf. “Vision I” in Roberts, 2007). These reasons are often reduced to national and economic considerations because of the general idea that advancement in science and innovations in technology form a basis for economic growth (Laugksch, 2000; McEneaney, 2003).

On the other hand, most of the contemporary rationales for SL rather focus on the perspective of an individual and citizenry. At least some scientific and technological understanding and skills are needed for very practical purposes in everyday life (Laugksch, 2000; cf. Shamos, 1995), and knowledgeable citizens are likely to be more confident, competent and successful in modern societies. Furthermore, since science and technology permeate virtually all aspects of society, laypersons must be able to participate intelligently and independently in decision-making processes that have a scientific or technological basis (Fensham, 2002; Jenkins, 1997; Laugksch, 2000; McEneaney, 2003). Issues of this kind that receive the greatest public attention are typically those that concern health, energy, natural resources, food, the environment, and so forth. This idea of SL, which Jenkins (1997) **refers to as “citizen science”, is congruent with the insights of the STS movement and the Socioscientific Issues (SSI) framework** (Zeidler, Sadler, Simmons, & Howes, 2005). Besides being seen as a prerequisite for ***participatory democracy***, SL is often regarded as a contributor to ***sustainable development*** (Holbrook, 2009), since a more scientifically literate population is more likely to make ethically wiser and more responsible decisions. As Bybee (2010) puts it, **science and technology education must be part of the response to “the grand challenges for citizens and societies”, such as climate change or health care. For some advocates, furthering SL is also a means of *redressing some social or economic injustices and imbalances* related to science and technology** (Jenkins, 1997).

Since the meanings of SL vary widely depending on these rationales, one must articulate a perspective when applying the concept. This dissertation employs a functional and contextualised interpretation of SL, focusing on ***citizens’ ability to identify, to form opinions and to make reasoned decisions on personal, social, and global issues related to science and technology***. Such an emphasis also appears in the highly influential PISA definition of SL (OECD, 2007), recent recommendations for European science education policies (Osborne & Dillon, 2008), and **“Vision II” for SL proposed by Roberts (2007)**. This conception of SL shifts the requirements associated with it towards a multidimensional form that commonly includes not only scientific content knowledge (terminology, facts and concepts), but also – and most importantly – procedural skills (manipulative and intellectual), dispositions (attitudes and behaviours), and an understanding of the relationships between science, technology and society, as well as the history and nature of science (Roberts, 2007; Wenning, 2006). Above all, SL is

considered as a functional ability (cf. Holbrook, 2010) rather than **knowledgeability in the traditional sense of ‘public understanding of science’** (see Stocklmayer & Bryant, 2012). Thus, the knowledge required must be relevant to citizens and situated in meaningful contexts (Jenkins, 1997; Roberts, 2007; Zeidler et al., 2005). Accordingly, the PISA definition distinguishes three contexts of SL – personal, social and global – in which **students’ functional use of knowledge is examined. The competencies central to this interpretation of SL are *identifying scientific issues, explaining phenomena scientifically*, and *using scientific evidence* (OECD, 2007).** These competencies require not only knowledge of the natural world, but also of science itself, including its nature and processes. Compared to the definitions of SL in the earlier PISA frameworks, the 2006 framework accentuates **students’ attitudes toward science, knowledge about science** and an understanding of the relationship between science and technology as integral parts of SL (OECD, 2007). These emphases are also evident in other recent views of science education for SL (Holbrook, 2010; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003; Roberts, 2007; Wenning, 2006).

Accordingly, the studies presented in this dissertation consider not only science content knowledge but also an understanding of the nature of science as well as of the interrelationships between science, technology and society to be central components of SL. The fields of NST are analysed in order to find such educationally important aspects in personal, social and global contexts. Functional SL is here considered to involve not only scientific but also technological issues⁷. Furthermore, the continuing debate on the implied **interpretations of the word ‘literate’ is addressed in article V. ‘Literate’, in its “fundamental sense”** (Norris & Phillips, 2003), refers to the ability to read and write, but it can also mean ‘learned’, or ‘competent’, or ‘able to function minimally in society’ (Laugksch, 2000).

2.3 BRINGING NST TO SCHOOLS: FACILITATORS AND BARRIERS

Teachers play a ‘make-or-break’ role in any curriculum innovation (Kelly, 2004). **Research has shown that teachers’ perspectives must be investigated** and taken into account in order to facilitate a reform of the curriculum or other changes in school practices (Anderson & Helms, 2001; Davis, 2003; Peers, Diezmann, & Watters, 2003; Roehrig, Kruse, & Kern, 2007; van Driel, Beijaard, & Verloop, 2001). Furthermore, particularly in Finland, teachers are deeply involved not only in implementing but also in formulating the curriculum, since the Finnish national standards leave room for teacher input (see e.g. Pehkonen, Ahtee, & Lavonen, 2007). It is therefore natural to

⁷ Many of the so-called ‘socio-scientific’ issues discussed in reference to SL are, in fact, primarily based on technology (see Shamos, 1995; Sjøberg, 1997). Thus, in the interpretation of SL adopted here, no distinction between scientific and technological literacies (Jenkins, 1997) can be made.

begin any process of curriculum amendment by considering teachers' conceptions. This view – making teachers engage in educational reforms in an early phase – is also widely supported in research (see e.g. Anderson & Helms, 2001; Clandinin & Connelly, 1992; Davis, 2003; Kelly, 2004; van Driel et al., 2001).

Accordingly, considerable research has been published on *facilitators* and *barriers* that affect teachers in their efforts to incorporate new contents or instructional methods in their teaching of science (e.g. Bamberger & Krajcik, 2010; Davis, 2003; Peers et al., 2003; Roehrig et al., 2007). While discussing the integration of technology into the classroom, Ertmer (1999) distinguished between *first-order barriers* and *second-order barriers*. The former are “**extrinsic to teachers and include lack of access to computers and software, insufficient time to plan instruction, and inadequate technical and administrative support**”, whereas the latter are “**intrinsic to teachers and include beliefs about teaching, beliefs about computers, established classroom practices, and unwillingness to change**” (p. 48). **This dissertation adopts Ertmer’s classification in the context of teaching specific content**, i.e. that relating to NST, and employs the terms *intrinsic* and *extrinsic barriers* in a manner similar to the recent study by Bamberger and Krajcik (2010).

The *intrinsic barriers* discussed in this research relate to teachers' knowledge, beliefs and self-efficacy regarding the teaching of NST. In related literature, **in-service training and teachers' networking have been shown to be effective in bringing down such barriers** (Bamberger & Krajcik, 2010; van Driel et al., 2001). The need for such teacher training programs on NST has **been surfacing worldwide; e.g., the “Big Ideas of Nanoscale Science & Engineering” project in the U.S.** has highlighted teacher preparation as a **significant challenge “to the goal of an NSE⁸-educated citizenry”** (Stevens et al., 2009, pp. 173-178). It seems clear that the professional training of teachers is a crucial facilitator for NST teaching at the secondary school level (cf. Akaygun, 2011; Bamberger & Krajcik, 2010; Healy, 2009; van Driel et al., 2001). However, basic university courses on these emerging fields have only been available in recent years, and the curriculum for pre-service science teachers holds hardly any NST (cf. Sederberg, Lindell, Latvala, Bryan, & Viiri, 2010). In Finland, little in-service training is being offered, either⁹.

Besides these *intrinsic barriers*, limited school resources for NST education were expected to create some barriers that are *extrinsic* to teachers. Previous research has shown that teachers generally face a considerable number of obstacles that prevent them from reforming their teaching (Peers et al., 2003). In the context of NST, a recent study by Bamberger and Krajcik (2010) pointed out that it is crucial to deal with extrinsic barriers such as time constraints, the need for change in standards, and the lack of instructional materials in order to enable NST teaching.

⁸ Nanoscale Science and Engineering.

⁹ As an exception, the University of Jyväskylä has systematically organised both pre-service and in-service courses (see <http://nanokoulu.net/en>).

According to a study carried out by Hutchinson, Bryan and Daly (2009) in the context of NST, the primary barriers perceived by teachers were extrinsic ones.

The Finnish (and similarly, the U.S.) secondary school curriculum does not explicitly refer to the fields of NST (FNBE, 2003; FNBE, 2004). Bamberger and Krajcik (2010) pointed out that time constraints essentially hinder NST teaching, since the topics are not elaborated in the curriculum (Stevens et al., 2009). The lack of time has been found to be a major barrier to the implementation of NST teaching (Hutchinson et al., 2009) and other innovations in the science curriculum (Peers et al., 2003). The Finnish national core curriculum does, however, **leave more leeway for teachers' and schools' own choices than**, for instance, the U.S. standards.

Another extrinsic barrier highlighted in related literature is the paucity of teaching materials. Although some instructional materials on NST have recently been developed (e.g. Stevens et al., 2009), hardly any textbooks are available that are suitable for the secondary school level, and none in Finnish. The educational materials on the Internet are also mostly in English¹⁰. Another challenge for teachers is the lack of instruments needed for conducting experimental work or inquiry-based activities. However, many kinds of classroom activities related to NST have been reported¹¹. **While 'real' instruments such as scanning tunnelling microscopes (STM)** are available for educational purposes at the academic level, their prices still make them unattainable for most secondary schools. An interesting solution for carrying out nanoscale measurements in the classroom is online remote access to an atomic force microscope (AFM) placed in a university laboratory (Jones et al., 2003; Sweeney & Seal, 2008).

2.4 INFORMAL AND OUT-OF-SCHOOL SETTINGS FOR LEARNING NST

As a consequence of the educational needs discussed in Chapter 1, settings for informal learning and public communication of NST have increasingly been discussed in the fields of social sciences, science education and science communication. Informal learning environments¹² have been suggested to have a significant potential not only to offer out-of-school learning opportunities but also to educate the general public about NST and promote the science-technology-society dialogue (Castellini et al., 2007; Crone, 2010; Zenner & Crone, 2008).

¹⁰ e.g. <http://www.nanochannels.eu/>; <http://nanoyou.eu/>; for a list of other examples see Murday (2009, p. 9)

¹¹ See e.g. Jones et al. (2003), Planinsic & Kovac (2008), Lindell & Viiri (2009), and a comprehensive collection of other examples in Sweeney & Seal (2008).

¹² **The term "informal" is here used simply to refer to "institutional settings other than (formal) classroom settings"** (Falk, Dierking, & Foutz, 2007, p. xix).

In general, the great importance of such settings has been widely recognized in the science education research community. The vast majority of all *life-long* and *life-wide* learning takes place outside the formal educational system (National Research Council, 2009, pp. 28-29), and informal learning environments play a key role in fostering scientific literacy (Falk, Storksdieck, & Dierking, 2007; Shamos, 1995). Learning in such informal contexts has been defined, for instance, as “learning that is self-motivated, voluntary, guided by the **learner’s needs and interests, learning that is engaged in throughout his or her life**” (Dierking, Falk, Rennie, Anderson, & Ellenbogen, 2003). However, not all learning that takes place outside the school is necessarily this **intrinsically motivated “free-choice learning”** (Falk et al., 2007). When such environments are used in school group visits, during school hours and according to the curriculum, they are rather out-of-school settings for formal education.

Informal and out-of-school learning environments cover a wide variety of institutional and/or everyday settings (see e.g. Rennie, 2007). This dissertation focuses on two specific settings: visits to museum or science centre exhibitions and industry site visits. Both settings are opportune contributors to NST education. The nature of science centres and museums matches the needs for enhancing public awareness of and engagement in NST (Crone, 2010), and offers ways for sidestepping many of the barriers that hinder NST teaching in the classroom (discussed in the previous section). Consequently, a number of NST exhibitions have been displayed throughout the world¹³. Site visits to nanotechnology-related enterprises are, in addition, an efficient and readily available means for advancing several educational goals outlined in Section 2.2. The characteristics of these learning environments are briefly discussed in the following.

Learning in museum exhibitions has been studied using a variety of theoretical frameworks, the sociocultural theory based on the work of Vygotski being the predominant one (e.g. Allen, 2004). Emphasising the sociocultural nature of learning, the Contextual Model by John Falk and Lynn Dierking (Falk & Dierking, 2000) is widely used to describe learning in museums. The model distinguishes 12 personal, social and physical factors that affect museum learning (Falk & Storksdieck, 2005). In this dissertation, the focus is mostly on the physical context of learning, i.e. on exhibitions and their development.

Here, a personal constructivist model is employed in order to describe the interaction of visitors with an exhibit. The Model for Personal Awareness of Science and Technology (PAST), proposed by Stocklmayer and Gilbert (2002), addresses the characteristics of exhibitions as learning environments

¹³ The U.S. Nanoscale Informal Science Education Network (<http://www.nisenet.org/>) involves a number of initiatives in science centres and museums. In the EU, the projects NANOTOTOUCH (<http://www.nanototouch.eu/>), NANOYOU (<http://nanoyou.eu/>) and Time for Nano (<http://www.timefornano.eu/>) have also recently brought NST contents to those environments.

as well as modern learning theory better than the much-criticized idea of ‘**public understanding of science**’¹⁴, which resembles the idea of the ‘**deficit model**’ (Wynne, 1993). The model for PAST has a personal constructivist perspective that is in line with the contemporary view of museum learning, in which the audience is no longer seen as a passive and undifferentiated ‘general public’ (Hooper-Greenhill, 1992).

According to the model, each individual has his or her own *personal awareness of science and technology (PAST)*, i.e. “a set of attitudes, a predisposition towards science and technology, which is based on beliefs and feelings and which is manifest in a series of skills and intentions” (Gilbert & Stocklmayer, 2001, p. 43). A science centre visit can induce *experiences* that **interact with visitors’ PAST**. These *experiences* are framed by any ideas, objects, events or processes that are retrieved from a **visitor’s memory when** (s)he uses an exhibit; Stocklmayer and Gilbert (2002) emphasise that these *reminders* form the basis for interpreting the exhibit. A fruitful *experience* triggers memories that are related to the scientific and technological ideas presented in the exhibition, and/or creates new memories that can later be used in understanding these ideas (Afonso & Gilbert, 2006). Through these subsequent, related *experiences*, **the visitors’ PAST** gradually evolves, eventually leading to an understanding of some scientific and technological ideas, products and their implications, i.e. the *target* of the exhibits.

Industry site visits are another form of out-of-school learning that is interesting with regard to NST education. An industry-related site visit uses a school–industry partnership or school–industry/business links. Research has shown several benefits of such visits: they offer cross-curricular perspectives, awaken and deepen interest in sciences, and show how sciences are applied (Parvin & Stephenson, 2004). Moreover, the students meet positive and diverse role models of scientists or workers in industry (Bruce & Bruce, 2000). **Such experiences from ‘authentic’ contexts support learning** as well as stimulate further studies or even a career in a field related to science and technology (Braund & Reiss, 2006). These advantages of site visits echo many of the aims of promoting scientific literacy that were discussed in Section 2.2. The collaboration also benefits industry by recruitment, contribution to the community and enhancing reputation (Parvin & Stephenson, 2004). Industry site visits have a long tradition in Finland, and they are recommended in the national core curriculum (FNBE, 2004).

However, connecting out-of-school visit practices to research has remained problematic (see e.g. Allen, 2004; Falk & Dierking, 2000; Grewcock, 2001; Lord, 2001; Schauble & Bartlett, 1997). This dissertation research attempted to bridge this gap and develop models for research-based practices concerning exhibition development as well as industry site visits.

¹⁴ For a recent critique of the traditional view of *public understanding of science*, see Stocklmayer & Bryant (2012).

3 RESEARCH PROBLEM AND METHODOLOGICAL FRAMEWORK

In order to address the educational needs discussed in the introduction, and to lay the groundwork for the development of teaching and learning of NST in schools and outside of them, the dissertation research aimed at addressing the following research problem:

What are the educational needs, possibilities and challenges of bringing the topics of NST to schools and out-of-school learning environments?

The research problem was approached by formulating three research questions, which are introduced and explained in the following section (3.1). Section 3.2 introduces the methodological framework of the study, and Section 3.3 presents the multi-methods approach selected to address the research questions. These methods are specified in Section 4.

3.1 RESEARCH QUESTIONS

RQ1. What is the role of nanoscience and nanotechnology (NST) in scientific literacy?

The first research question aimed to map the general need for NST education for all, and analyse which aspects of NST are educationally significant. Thereby, RQ1 laid the groundwork for the closer scrutiny of NST education both in schools and out-of-school settings. In order to answer RQ1, theoretical-analytical as well as empirical approaches were employed in the studies reported in articles **I** and **II**.

RQ2. How do science teachers perceive the possibilities of NST education in secondary schools?

As discussed in Section 2.3, teachers play a key role in any curriculum innovation and their views should be taken into account in an early phase. Therefore, the second research question focused **on science teachers' views of** the appropriateness of NST for secondary school curriculum content and the resources for teaching these topics. The teacher surveys addressing RQ2 are reported in articles **II** and **III**.

RQ3. What guidelines does science education research give for the development of NST education in secondary school and in out-of-school settings?

On account of the practical value of the thesis, this last research question aimed at presenting research-based suggestions for the planning of NST education on the basis of the previous literature and new supplemental studies. Besides scrutinizing the secondary school curriculum, informal learning environments for NST were additionally addressed. As discussed in Section 2.4, they have an important role in augmenting formal education in NST through out-of-school visits, and in responding to the public interest and promoting adult awareness of these fields. Research-based suggestions for the development of such settings are reported in articles **III (teachers' perception of the need for out-of-school settings on NST)**, **IV (science exhibitions)** and **V (industry site visits)**.

3.2 THE MODEL OF EDUCATIONAL RECONSTRUCTION

The research questions were approached using the Model of Educational Reconstruction (Duit et al., 2005; Duit, 2007) as the methodological framework. The model was designed with the specific purpose of providing a **“theoretical framework for studies as to whether it is worthwhile and possible to teach particular areas of science”** (Duit, 2007, p. 5). Accordingly, the model has previously been employed in scrutinising comparatively novel fields of science – ones that are not yet in the school curriculum. For example, Duit, Komorek and Wilbers (1997) applied the model to the case of chaos theory, and Komorek and Duit (2004) continued this by reconstructing the domain of non-linear systems. On the basis of these previous cases, the model also appears to be suitable for addressing the educational concerns introduced in Chapter 1, and in analysing the emerging fields of NST from an educational perspective. The MER approach falls within the philosophical tradition of curricular inquiry, which **asks whether “children should be taught certain things or in certain ways, based on what we believe are just and appropriate educational goals and means”** (Darling-Hammond & Snyder 1992, p. 41).

The Model of Educational Reconstruction, associated with the *design research* tradition, combines analytical and empirical educational research with the development of practical educational solutions. The model was developed in the mid-1990s by Reinders Duit, Harald Gropengiesser, Ulrich Kattman and Michael Komorek, and is based on a continental European view of science education and the German educational tradition (Duit et al., 1997). One of the fundamental ideas of the model is that the content structure for instruction cannot be taken directly from the science content structure, but has to be specially (re)constructed by paying attention to the educational

goals as well as students' cognitive and affective perspectives (Duit et al., 1997; Duit, 2007; Komorek & Duit, 2004).

MER has a moderate constructivist orientation in two aspects. Firstly, learning is seen as an active construction process by individuals, based on their pre-existing knowledge. Therefore the development of learning **environments requires an awareness of learners' prior conceptions. Secondly**, scientific knowledge is considered as a human construction. According to this epistemological position, a field of science does not have any 'true' content structure for instruction; all the presentations of the content are subjective reconstructions based on certain aims. Thus, the content structure for science education must also be reconstructed from educational aims and concerns rather than derived solely from science issues (Duit et al., 1997; Duit, 2007; Komorek & Duit, 2004; van Dijk & Kattmann, 2007).

According to the model, when developing educational solutions, science content matters and students' conceptions must be equally taken into account and carefully linked together (Duit, 2007; van Dijk & Kattmann, 2007). Figure 1 depicts **the model's three components** – 1) analysis of content structure, 2) research on teaching & learning, and 3) development and evaluation of instruction¹⁵ – and their close interplay. It is essential in MER that knowledge gained in one of the components influences the progress and conclusions in the two other components.

Previously, MER has been employed in developing teaching–learning sequences for several physical topics (see e.g. Duit et al., 1997; Komorek & Duit, 2004; Nurkka, 2006). The model has also been used in teaching at the university level, where educational reconstructions have been carried out to create a physics laboratory course for university students (Neumann, Schumacher, & Welzel, 2005), and to improve physics teacher education (Aiello-Nicosia, 2000). More recently, MER has been applied in developing a further model for science teacher education (van Dijk & Kattmann, 2007). All these previous applications of MER have dealt with formal educational settings. The present dissertation explores the potential of the model in the development of informal learning environments.

¹⁵ From here onwards, the third component is referred to as 'Development of learning environments', since this title better fits the model's use in this dissertation.

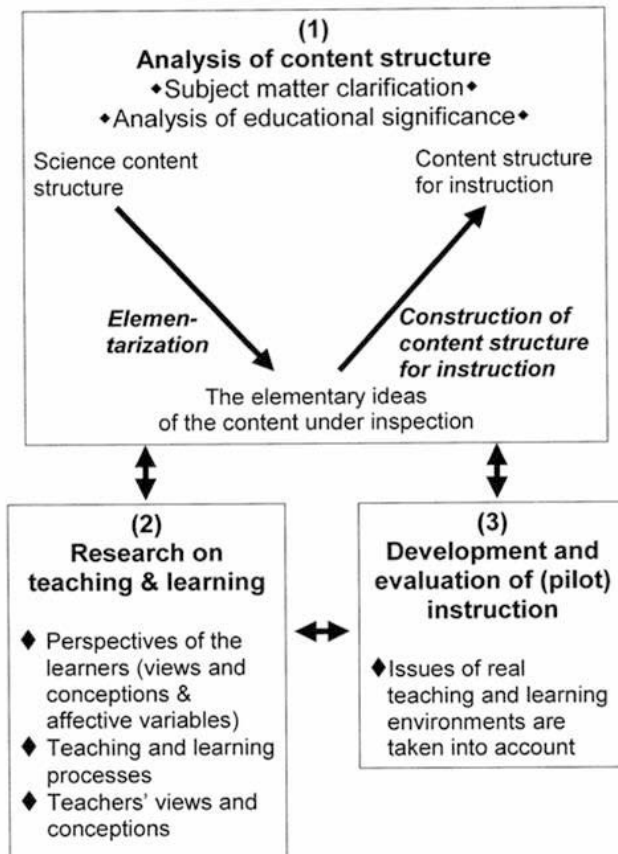


Figure 1 The Model of Educational Reconstruction (Duit, 2007, p. 6). Reprinted by permission of the EURASIA Journal.

3.3 MULTI-METHOD APPROACH

Research on broad and complex social phenomena typically requires multiple methods. The research problem and research questions of this dissertation research took a broad perspective and aimed at a holistic view of the opportunities and challenges of NST education in a variety of educational settings. Thus, the research frame clearly called for triangulation (cf. Cohen & Manion, 1994).

Triangular techniques, i.e. the use of mixed methods, are helpful in overcoming the problem of ‘method-boundedness’ that is typical for all social sciences (Brewer & Hunter, 1989; Cohen & Manion, 1994). Since the methods used are not neutral or atheoretical (as discussed in the following and in the articles), the use of a variety of approaches that have complementary strengths and nonoverlapping weaknesses (Johnson & Christensen, 2004) builds confidence in the validity of the results and conclusions. This dissertation adheres to the *compatibility thesis* and

pragmatist philosophy, i.e. considers that quantitative and qualitative methods can be mixed in a pragmatic way in order to find answers to research questions (Brewer & Hunter, 1989; Johnson & Christensen, 2004).

The variety of studies in this dissertation research enabled not only methodological triangulation, but also multiple levels of analysis (Cohen & Manion, 1994). The same problems were scrutinized at the individual and group levels, as well as the level of society.

Triangulation is inherent in the Model of Educational Reconstruction, which draws on both analytical and empirical, and both content-centred and learner-centred research, and utilizes them in combination. In Figure 2, the studies carried out in this dissertation are situated within the three components of the MER. The methods of the studies are introduced in the following sections.

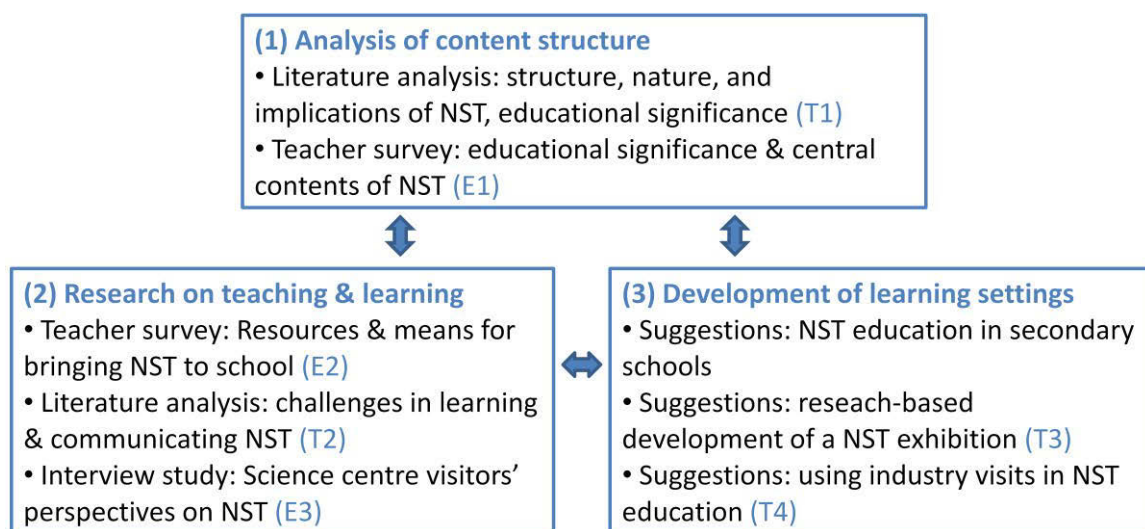


Figure 2 The theoretical studies (T1-4) and empirical studies (E1-3) of the dissertation situated in the Model of Educational Reconstruction.

In order to answer research question 1, and to lay the groundwork for answering research questions 2 and 3, both theoretical and empirical analyses were carried out in the first component of the MER, “**Analysis of content structure**” (see Fig. 2). Here, “**content structure**” is understood in a broader sense than usual (Duit, 2007): educational reconstruction must encompass not only scientific concepts and principles, but also the nature and methodology of the field in question, as well as its relevance to everyday life and society in general. Analysis of subject matter and its educational significance in the MER is mainly based on content and text analyses and also draws on philosophy and the history of science (Duit, 2007; van Dijk & Kattmann, 2007). Thereby, the NST content analysis started with an analytical-theoretical study (T1 in Fig. 2). Furthermore, the analysis of content structure in the MER can employ not only hermeneutic-analytical

but also empirical methods, such as expert questionnaires or Delphi studies (Duit, 2007, p. 8). Accordingly, here the educational significance of NST was also analysed empirically (E1 in Fig. 2) by surveying science teachers trained in NST content knowledge. In order to answer research question 1, the results of these theoretical and empirical analyses were compared to each other in the light of the literature presented in Sections 2.1 and 2.2. The methods are described in Sections 4.1 and 4.2 and the results are summarised in Section 5.1.

The second component of the MER, **“Research on teaching & learning”**, included a literature review and two empirical surveys (see Fig. 2). The aforementioned survey of NST-trained teachers (E1) was complemented with a larger, quantitative study using an online **questionnaire (E2) focusing on teachers’ views of the possibilities for NST instruction in secondary school**. In the theoretical part, science education literature that deals specifically with the teaching and learning of nanoscale science was reviewed (T2). According to the MER, as well as a myriad of educational studies, finding out typical learning difficulties and instructional challenges is crucially important when planning any kind of education. The results of this review were especially used in answering research question 3. As discussed in article **IV** of the thesis, such content-specific science education research findings can be helpful not only in the development of formal education but also informal learning environments. The literature analysis was complemented with a survey of **science museum visitors’ perspectives on NST (E3)**. The results of these studies were used in answering research questions 2 and 3.

In the third component of the MER, **“Development of learning environments”**, research question 3 was addressed by forming research-based suggestions for the planning of education on NST at the secondary level and in out-of-school settings (see Fig. 2). Suggestions concerning the incorporation of NST into the secondary school curriculum draw on all the theoretical and empirical studies carried out within components 1 and 2 of the MER. According to the MER, the development of instructional approaches must be based on close scrutiny of the science content and the perspectives of teachers and students (Duit, 2007). Thus, results from the theoretical analysis of educational significance (T1), both teacher surveys (E1 and E2) and the literature review on NST-related learning difficulties (T2), as well as the visitor interviews (E3) are all elaborated and synthesized here to reach some conclusions and provide recommendations. In addition to these studies, suggestions on the development of out-of-school settings require a closer examination of the characteristics of such environments (cf. Duit, 2007). The last two theoretical studies, T3 and T4, focused on the two settings for out-of-school learning that were selected as cases in this dissertation: museum exhibitions and industry sites (see Section 2.4). The studies suggest research-based models for the development of such learning environments that can be used to augment classroom teaching on NST.

4 METHODS

4.1 LITERATURE ANALYSIS T1

The theoretical-analytical part of the content-centred component of the MER (T1 in Fig. 2) involved an analysis and synthesis of several domains of literature on NST. Firstly, to clarify the content structure of this emerging field, the analysis spanned the few heretofore-published academic textbooks on NST (e.g. Nalwa, 2004; Poole & Owens, 2003). Secondly, the nature and social aspects of the field were analysed from the critical perspective of Science, Technology and Society (STS) studies. Despite the novelty of NST, during the past decade there have been a number of publications employing philosophical, historical, analytical and ethical approaches to study these emerging fields (e.g. Baird et al., 2004; Brune et al., 2006; Cameron & Mitchell, 2007; Hunt & Mehta, 2006). The literature analysed included a range of philosophical as well as social studies on NST (for a closer examination of the literature analysed, see article **I**). On the basis of this analysis, the educational significance and central contents of NST were discussed in relation to the general goals of science education. These goals were studied by reviewing a number of conceptual overviews, acknowledged definitions and recently suggested frameworks for scientific literacy (e.g. Fensham, 2002; Laugksch, 2000; Linder, Östman, & Wickman, 2007; McEneaney, 2003; Norris & Phillips, 2003; OECD, 2007; Roberts, 2007; Shamos, 1995; Sjøberg, 1997). By this (deductive) approach, the study aimed at answering research question 1 on the role of NST in scientific literacy as defined in Section 2.2. The results are presented briefly in Section 5.1, and thoroughly in article **I**.

4.2 TEACHER SURVEY E1

The theoretical analysis T1 was complemented with the empirical part of the content-centred component (E1 in Fig. 2), **in which science teachers' views** on the educational significance of NST were surveyed. In order to ensure the competence of the respondents in NST-related questions, they were first trained in a week-long course headed “**Nanoscience and nanotechnology**”, arranged in June 2008 by the Department of Physics at the University of Helsinki. The course aimed at introducing the various aspects of the extensive field of NST, including not only scientific concepts and their relationships but also knowledge on the nature and processes of NST as well as interrelationships with society, in a comprehensive and balanced way (see the detailed description of the course in article **II**). The course strongly focused on *content knowledge* rather than *pedagogical content knowledge*

(Shulman, 1986) of NST, and the educational significance of NST was left to the teachers to contemplate by themselves.

The study employed *purposeful sampling*: by selecting *information-rich cases*, one can gain especially valuable, in-depth knowledge of the issues that the study is mainly focused on (e.g. Miles & Huberman, 1994; Patton, 1990). Indeed, the respondents in this study could be considered as experts concerning prospects of NST education for all. Firstly, they had considerable working experience as teachers, and were therefore very familiar with the general educational goals. Secondly, due to the in-service training course the respondents were clearly more aware of and informed about the fields in question than Finnish school teachers on average. Therefore, the respondents were especially competent in analysing NST from an educational viewpoint and estimating the *educational significance* of the fields, considering general educational goals and the relevance of the topics to society and to the students themselves (cf. Duit, 2007; Komorek & Duit, 2004).

The survey employed a questionnaire with open-ended questions, constructed in such a way as to help the respondents ponder the issues related to NST education at secondary school from several viewpoints. During the final day of the course, 23 participants completed the questionnaire with open questions on various aspects of NST education (see the questionnaire in Appendix A of article **II**). The questionnaire was designed in a way that avoids giving suggestions to the respondents. Qualitative content analysis on the returned questionnaires aimed at identifying and categorising similarities in responses (cf. Patton, 1990), i.e. finding patterns that characterise the **respondents' ideas**. **Every answer form** was analysed as a whole, so that it did not matter which questions the respondents had written their responses to; the purpose of the various questions was simply to make the respondents think about the issues from various perspectives. First, three general themes in the **teachers' responses** were identified: the perceived need and reasons for NST education, ideas for important content areas, and opinions on the resources for NST instruction. The analysis was then carried out by scrutinising all of the gathered responses from the viewpoint of each of these themes in turn. Sections 5.1 and 5.2 summarise the results, which are presented in detail in article **II**.

The 23 respondents of the study did not represent any larger group of teachers. As discussed above, the choice of a qualitative approach and *purposeful sampling* was driven by conceptual questions, not by concerns for representativeness (cf. Miles & Huberman, 1994, pp. 27-34). Together with the results of the theoretical analysis, however, the respondents' **views** provided a solid basis for answering research question 1 and laying the groundwork for the development of NST education.

4.3 TEACHER SURVEY E2

In order to determine **science teachers' views** on the possibilities of NST education in secondary schools (research question 2), the aforementioned survey of NST-trained teachers (E1) was complemented with a larger, quantitative study using an online questionnaire with mostly closed questions (E2). The instrument was developed on the basis of theoretical problem analysis and earlier teacher surveys (see article **III**). The respondents (n = 107) were Finnish physics, chemistry and mathematics teachers, typically with no specific training on NST. The focus of this study was on the **teachers' perceptions** of their own **resources and their schools' resources** for providing education in NST. The questionnaire also included questions on the need for out-of-school learning environments related to nanoscience, which was also interesting in relation to research question 3.

While E1 used data-driven **qualitative content analysis of the teachers' responses** (as discussed in the previous section), E2 employed a quantitative theory-driven approach. The questionnaire (see Appendix A in article **III**) was developed on the basis of earlier surveys and literature on barriers and facilitators for curriculum change (see Section 2.3). The questions aimed at determining **teachers' perceptions of their own resources for NST teaching (intrinsic barriers)**, **their schools' resources for providing education in NST (extrinsic barriers)**, and ways for overcoming both kinds of barriers (**facilitators**). These views were enquired with 22 multiple-choice questions. In addition, the questionnaire included three background questions and three open-ended questions. The invitation to complete the online questionnaire, secured with an invitation code, was e-mailed to the members of **the Finnish Mathematics and Science Teachers' Association (MAOL)**. During the survey period of two weeks in late 2009, a total of 107 teachers anonymously responded to the questionnaire. The responses to the multiple choice questions were analysed by simple descriptive statistics (Johnson & Christensen, 2004), and the responses to the open-ended questions were used to interpret these quantitative results.

The sample of this study did not represent an average Finnish science teacher: there was a bias towards those who are more interested in answering surveys in general, and in NST and NST education in particular. This bias can, however, be seen as convenient rather than problematic, since such active and interested teachers are ultimately also those who are likely to work together with the research community in the early stages of curriculum revision. The results of study E2 are presented and briefly discussed in Section 5.2 (in detail in article **III**).

4.4 LITERATURE ANALYSIS T2

The literature analysis T2 involved science education research literature on teaching and learning the nanoscale concepts, including studies on typical learning difficulties and educational challenges related to this content. Only a quite limited (although rapidly growing) amount of such research has been published, so it was not very problematic to demarcate the literature to be analysed. The analysis spanned a comprehensive book on NST education (Sweeney & Seal, 2008) and a recent review article (Hingant & Albe, 2010), and all the science education research publications the latter refers to. A few common themes clearly emerged from the literature, and the analysis focused on these. The results are presented in Section 5.3 and their implications for the development of NST education are discussed in Section 5.4 and in Chapter 7. The results of this review were used in answering research question 3.

4.5 INTERVIEW STUDY E3

Literature analysis T2 was complemented with a survey on science museum **visitors' perspectives on NST (E3)**. The survey was conducted in the form of a standardized open-ended interview (Patton, 1990). The sequence of questions is presented in Appendix A. The beginning of the interview aimed to determine the level of awareness of the respondent about NST. Since public awareness of these emerging fields was presumed to be quite low, in the latter part of the interview some descriptions were given to the respondents in order to help them consider the meanings of NST. These descriptions, given similarly to each respondent, are also presented in Appendix A. Furthermore, the survey aimed at learning about the specific communicational challenges related to the use of visualisations of nanoscale objects. To that end, an image and a video were shown to the respondents together with some explanations and questions (see Appendix A). In addition to the interview, the respondents were asked to provide background information in a brief questionnaire: gender, age, educational background, general interest in science, and general interest in technology (the latter questions had a four-point rating scale).

Interviews were carried out in the lobby of the Finnish science centre **“Heureka”** on 16th-17th August 2008. The interviewees were randomly selected from among the adult visitors. The interviews took about ten minutes on average, including the completion of the background questionnaire. The number of interviewees was 28, with 15 women and 13 men. The age of the respondents varied from 20 to 62 years, with a quite an even distribution. The educational background varied from secondary school to the university level. The **great majority (93%) were at least “quite**

interested” in both science and technology, as could be anticipated for science centre visitors.

The interviewees’ responses were analysed by identifying a few answer categories per question and categorizing the respondents’ answers in these categories (Miles & Huberman, 1994; Patton, 1990). Due to the small sample, no strong generalizations can be made concerning the general public or even the visitors to the science centre. However, together with the results of the literature analysis, the results are useful in gaining a tentative insight into the awareness and interest of laypersons regarding NST, and some idea of the educational and communicational challenges concerning nanoscale issues.

4.6 THEORETICAL STUDY T3

The last two studies of the dissertation were theoretical suggestions dealing with the development of out-of-school settings that could contribute to scientific literacy in the context of NST. The first of these, study T3 (article **IV**), addressed exhibitions in science centres and museums. On the basis of literature on museum learning (e.g. Allen, 2004; Falk & Dierking, 2000; Grewcock, 2001; Lord, 2001; Mortensen, 2010; Schauble & Bartlett, 1997), the study called for greater use of educational research in the development of exhibitions in order to support the educational function of these environments. A model for incorporating educational research in this process was suggested and discussed. The proposed model adapts the Model of Educational Reconstruction (discussed in Section 3.2) for the purpose of exhibition development following the idea of the Model for the Personal Awareness of Science and Technology (discussed in Section 2.4). The former model identifies the domains of literature and the types of research that can be used in the process, whereas the latter model specifies the purposes of **those studies in terms of supporting visitors’ learning** experiences with the exhibits. This argumentation, put forth in article **IV**, was based on an analysis and synthesis of the literature on learning in exhibitions and the prior use of the MER in formal science education. After suggesting the general model, the study moved on to apply it to the development of a prospective exhibition on the field of NST. The development process employed all the research methods presented above in sections 4.1–4.5 and the results of these studies in order to identify apt strategies for presenting NST in an exhibition. This procedure is summarised in Section 5.4.1.

4.7 THEORETICAL STUDY T4

Theoretical study T4 developed a research-based model for organising another type of out-of-school learning activity: an industry site visit for lower secondary school science education. The model aims at enhancing a certain

kind of scientific literacy, and it can be applied to NST education by choosing nanotechnological companies as targets of the visits. The study analysed the potential of such visits and related learning activities, such as inquiry activities and **learning by reading and writing, in enhancing students'** scientific literacy. The key ideas of the study are summarised in Section 5.4.2, and the whole study is published in article **V**.

The design of the model followed the Design-Based Research approach (DBR) (Design-Based Research Collective, 2003) as a methodological framework. DBR is a general framework for the design, development, implementation and evaluation of learning activities. It uses a pragmatic frame and emphasises three aspects: 1) a design process is essentially iterative, starting from the recognition of the need to change praxis, 2) it generates a widely usable artefact, such as learning activities, teaching modules or environments, 3) and it provides educational knowledge for more intelligible praxis.

Theoretical problem analysis included literature on scientific literacy (see Section 2.2), site visits as out-of-school learning activities (see Section 2.4), **students' interest** in and attitudes towards science (e.g. Osborne, Simon, & Collins, 2003), and Predict-Observe-Explain (POE) activities. The analysis of motivational aspects of an industry site visit was based on the Self-Determination Theory (SDT) by Deci and Ryan (2000). The model was suggested on the basis of the theoretical analysis. Empirical problem analysis (Edelson, 2002) involved several design and production cycles: the design of a prototype, evaluation of the prototype, and re-design.

5 RESULTS

5.1 THE ROLE OF NST IN SCIENTIFIC LITERACY

This section summarises the results of the theoretical and empirical studies (T1 and E1 in Fig. 2) that were carried out to answer the first research question, i.e. to map the educational significance and central educational contents of NST in terms of scientific literacy.

The theoretical analysis is presented in article **I**. Several social as well as epistemological aspects of NST were identified, which render these fields educationally interesting and relevant to scientific literacy as interpreted in Section 2.2. As nanotechnology raises important socio-scientific and ethical issues regarding society, the environment and public health, citizens need to be able to deal with these issues in an informed, responsible and independent manner. Science education should therefore stimulate debate on NST in order to prepare students for decision-making. Furthermore, article **I** argues that scientific literacy in the context of NST requires an understanding of the nature of NST as well as its social dimensions. Some special features in the processes of NST should be addressed in education in order to represent the nature of the fields properly. These features include the interdisciplinary character of the fields in question, the entwined relationship between nanoscience and nanotechnology, and the interplay between empirical and theoretical research with distinctive roles of modelling, simulations and imaging. Altogether, the results suggest that science education in general could use NST as a subject matter in order to evoke dialogue on important contemporary issues related to science, technology and society, and to provide up-to-date views on the nature of science¹⁶.

In the empirical part of the analysis (E1, article **II**), **the teachers' views** supported the conclusion of the theoretical analysis: NST is an educationally significant field and plays an important role in up-to-date scientific literacy. On that account, the in-service training course participants considered NST as providing desirable content for secondary school, while pointing out several difficulties in arranging instruction on them in practice (these challenges are further discussed in the following section). According to the teachers, particularly the applications and products of NST, which are becoming increasingly important in everyday life, should be taught to all citizens. At least some level of understanding of NST-related risks and potential benefits regarding public health and the environment was considered as an important part of scientific literacy. Understanding of the nanoscale phenomena itself – including the scientific principles, scale

¹⁶ The interdisciplinary nature and the societal visions of NST are further discussed, from an educational viewpoint, in another publication (Laherto, 2010).

conception, research methods and manufacturing techniques – was also considered educationally significant. The respondents did not, however, consider quantum mechanics as a necessity when discussing NST in secondary school. This is interesting, since the phenomena and properties that make NST scientifically and technologically novel are essentially caused by *quantum effects* (except for the phenomena based on the classically understood *scaling effects*; see Brune et al., 2006). However, the position of the teachers is understandable given their view of the purpose of NST education for all. It can be argued that the social and environmental implications of NST, for example, can be grasped without the scientific explanations for the discontinuous change in properties at a certain size. NST education for scientific literacy could thus remain at the level of macroscopic manifestations of nanoscale phenomena, together with their implications.

Both the theoretical and empirical analyses highlighted the meaning of NST education for everyday life and citizenship, and the rationales pointed out are in line with the general demands for NST education discussed in Chapter 1, and especially with Roberts' (2007) **“Vision II” of scientific literacy** (see Section 2.2). Educationally significant aspects were identified within personal, social and global contexts. Knowledge *about* NST is at least as important as knowledge *of* NST: according to the analysis, NST plays a role in scientific literacy especially due to the prospective societal implications¹⁷ and the postmodern nature of the field. The field also seems important **regarding students' further studies and working life. Moreover, since NST** has generated broad public interest and media attention, addressing these topics in school may also indirectly contribute to scientific literacy by motivating young people to study related disciplines in general. The decline of interest in science studies is chiefly due to the disconnect between school **science and students' preoccupations, and also the absence of modern sciences** in curricula (see Osborne, 2007). Thus, emerging fields such as NST are also noteworthy with respect to the motivational factors that drive scientific literacy.

5.2 TEACHERS' VIEWS OF POSSIBILITIES FOR NST EDUCATION IN SECONDARY SCHOOLS

Research question 2 was approached through two teacher surveys. While the first survey (E1 in Fig. 2) mainly focused on the views of NST-trained teachers concerning the educational significance of NST (research question 1, discussed in the previous section), it also included questions about the practical possibilities and resources for bringing NST into secondary schools. The second survey (E2) was more directly focused on research question 2.

¹⁷ In the second teacher survey, E2, the respondents also estimated the societal influence of NST to be substantial in the near future, and recommended the basics of NST to be taught at school.

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These findings, reported in articles **II** and **III**, are briefly summarized and discussed in the following.

Despite the different types of sample and analysis, studies E1 and E2 (articles **II** and **III**) provided quite a consistent image of the current state and prospects of NST education in secondary schools. Although the respondents considered that NST should be discussed in school, this currently happens in their lessons only rarely and in passing. This is at least partly due to the fact that the Finnish secondary school core curriculum does not refer to the fields of NST explicitly (FNBE, 2003; FNBE, 2004). **Discussing them depends fully on teachers' own activity and interest** – and according to the respondents, there is little room for extra-curricular contents. The respondents in both studies emphasized that addressing NST more than incidentally would necessitate a change in national curriculum standards. This barrier seems to be as central as in the U.S. (see Section 2.3), despite the greater leeway of Finnish standards. Nevertheless, in study E1 many respondents pointed out the close relationships of the educationally significant NST concepts with the current science curriculum. Accordingly, the teachers in both studies preferred the incorporation of NST as a transdisciplinary theme in the context of current science subjects, and pointed out the potential of NST to integrate the traditional disciplines and approaches. These ideas are further elaborated in Chapter 7.

Besides the curricular constraints, in both studies E1 and E2 the teachers pointed out many other barriers that also hinder bringing NST into science lessons. School resources for NST teaching are poor, if not nonexistent (E2). Those barriers that are *extrinsic* to teachers could, according to both studies, be lessened with ready-to-use teaching and learning materials such as textbooks, DVDs, online applications and tutorials (almost no resources are currently available in Finnish), and additional resources for laboratory equipment (half of the respondents in E2 stated that currently there are no possibilities for **experimental work**). **The teachers' ideas on the time constraints** due to curricular issues and other *extrinsic* resources for NST teaching correspond with the views of American teachers in the recent studies by Hutchinson, Bryan and Daly (2009), and Bamberger and Krajcik (2010).

In E2, the teachers estimated their own resources for NST teaching as poor, but still slightly better **than their school's resources**. **The respondents** may, due to the sampling discussed earlier, have fewer *intrinsic barriers* for teaching NST than the average teacher. Regardless, the teachers in both surveys highlighted the need for in-service training on NST. They also seem willing to attend such courses (E2). **Teachers' unwillingness to change practices** – a barrier postulated by Ertmer (1999) – does not seem as crucial an obstacle among these respondents. On the basis of the results of E2, in-service courses should address not only content knowledge of NST but also, and perhaps even more importantly, pedagogical content knowledge (see article **III**, p. 8). The effectiveness of professional development courses in

facilitating curriculum innovations and bringing down *intrinsic barriers* has also been widely reported in the international literature (Akaygun, 2011; Bamberger & Krajcik, 2010; van Driel et al., 2001). The teachers surveyed in this dissertation research perceived the same need for teacher training that has been surfacing worldwide (see e.g. Stevens et al, 2009, pp. 173–178).

In the latter teacher survey (E2), teachers were also asked to suggest different means for providing education on NST. As a result, out-of-school learning environments were considered as an attractive alternative for **classroom teaching. Most of the teachers were at least “quite interested”** in bringing students, for instance, to a nanotechnology company or a museum or science centre exhibition on NST. On this basis, it seems that school–industry collaboration has a good potential, and museum exhibitions could also function as targets for school group visits. These opportunities are discussed in the following when addressing the final research question.

5.3 CHALLENGES IN LEARNING AND COMMUNICATING NST

The main results of the literature analysis of teaching and learning NST (T2) and the interview study (E3) are summarised in this section. These results are not reported in detail in articles **I–V** but in a forthcoming conference publication (Laherto, 2012). Some of the results are, however, included here since they support answering research question 3 on the research-based development of education on NST at the secondary level as well as in out-of-school learning environments. This research question is also addressed through the results of the studies on the educational significance of NST and **teachers’ perspectives (T1, E1 and E3)**.

Analysis of the literature on NST teaching and learning (T2) revealed that various studies have quite coherently pointed out certain challenges in understanding the nanoscale and its concepts. Several studies have shown that people of all ages have major problems in understanding the scale of NST (Castellini et al., 2007; Tretter, Jones, Andre, Negishi, & Minogue, 2006). In their study on the understanding of the size and scale of objects among students (of various ages) and experts, Tretter et al. (2006) concluded (not surprisingly) that students tend to have greater problems with scales for which they have no direct experience, especially microscopic and sub-microscopic scales. However, the size conceptualisation seems to be easier using relative comparisons than absolute sizes. Moreover, size landmarks, or points of reference, seem to be an important tool for anchoring conceptions of spatial scale (Tretter, 2008).

Besides the fact that the scale itself is difficult to comprehend, an additional challenge in NST communication arises because the public does not have a good grasp of the terminology and concepts regarding atoms and molecules and lacks knowledge of the atomic structure of matter (e.g. Crone,

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2010; Stevens, Delgado, & Krajcik, 2010). It is common to conceptualize matter as being continuous rather than particulate. Children use the terms ‘atom’, ‘molecule’ and ‘cell’ very ambiguously, and have many misconceptions (Murriello, Contier, & Knobel, 2006). Additionally, students tend to use ‘scaling’ erroneously (and this may be made worse by using macroscopic models of nanoscale phenomena) and assume that atoms/molecules have the same properties as the macroscopic substance they are part of.

Castellini et al. (2007) have argued that a major challenge in public communication of NST is that scientists – and also educators – tend to erroneously assume that lay people are familiar with the basic ideas of the structure of matter and able to comprehend the size scale. An understanding on nanoscale phenomena can, however, only be built on a comprehension of atoms as building blocks. Therefore, although it may be argued that the most essential ideas of NST involve scale only indirectly (see Section 2.1), learners need to familiarize themselves with the basics of the scale and the structure of matter before going into actual topics of NST.

Since the behaviour of nanoscale particles is governed by quantum effects, discussion of this behaviour in proper terms requires highly sophisticated concepts. This certainly poses educational challenges and risks of generating misconceptions (Sabelli et al., 2005). Careless simplification of the sophisticated concepts of NST, especially in quantum mechanics, leads to superficiality and the risk of misrepresentation.

The extensive use of images in communicating nanoscale objects and phenomena has recently also become an educational research interest (e.g. Landau, Groscurth, Wright, & Condit, 2009). The common conception of **nanoscience “making atoms visible” is alleged to be problematic** (Pitt, 2004), since the microscopy used in nanoscale research is epistemologically not an outright continuation of instruments such as the telescope or light microscope. The scanning force microscope, the atomic force microscope and the scanning tunnelling microscope simply do not portray the visible properties of an object in the sense of geometrical similarity and realistic depiction of colours. Rather, these techniques serve certain theoretical models, but do not generate an empirical database in the same sense as telescoping and light microscopy do (Brune et al., 2006; Lenhard, 2004; Pitt, 2004). Brune et al. (2006, pp. 53–57) also argue that the discourse on NST in general is replete with apparent confusion of models with descriptions of reality due to nanoscientists who tend not to emphasise that their representations are relevant only in the framework of certain theories, models, methodological decisions and purposes. Consequently, models are confused with what is being modelled.

The results of the survey E3 supported many of the aforementioned findings of the literature analysis. Only some of the interview results, namely those that are useful in answering research question 3, are mentioned here¹⁸.

Almost all of the respondents (96%) had heard of or read at least something about nanoscience and nanotechnology, the mass media (newspapers, television and popular science magazines) being the most important sources of information. When asked about their conception of the **meaning of “nanoscience and nanotechnology”, 71% of the respondents coupled the terms with some kind of “smallness”**. Every fourth interviewee even mentioned the level of atoms or molecules here. On the other hand, 50% of the respondents associated NST with new technological products, e.g. faster computers, stronger materials and tiny robots.

As the visitor survey was expected to give an additional insight into the educational challenges discussed in the literature analysis, the questions **regarding visitors’ perceptions** of the scanning tunnelling microscope image¹⁹ (see Appendix A) were of special interest. Firstly, without any explanation the respondents were asked to interpret what is depicted in the image. Only 25% of the interviewees named any nanoscale objects (molecules, atoms etc.), whereas most of the respondents associated the image with either **macroscopic objects (35%) such as “an island” or “a waterdrop” or microscopic objects (29%) such as “a cell”**. After the respondents were told that there is a ring of iron atoms on a copper surface and the diameter of the ring is ca. 7 nanometres, 25% of the respondents knew that the image had been created with an electron microscope, whereas 36% suggested that it had been made by computer modelling, without experimental instruments. After this, the interviewer told that it was a STM image, briefly explained the operating principle of STM, and then asked the respondent to say something about the iron atoms or the copper surface. Even after this attempt for a contextualization, most of the respondents (57%) came up with false, macroscopic conclusions about the image, for example suggesting that the **copper surface is “rough”, “soft” or “jelly-like”, or that the iron atoms are “sharp” or “rusty”, or that “iron is warmer than copper”**. Although many respondents reached fully proper conclusions about the nanostructure, the findings support the conclusion of the literature review, implying that special attention has to be paid when communicating the nanoscale using electron microscope images, in order to avoid misleading learners into false models of direct sense perception and epistemological misunderstandings.

¹⁸ More results are reported in a conference publication (Laherto, 2012).

¹⁹ The image that was shown to the respondents is also on the cover of the printed version of this dissertation.

5.4 DEVELOPMENT OF SETTINGS FOR OUT-OF-SCHOOL LEARNING OF NST

Out-of-school learning typically has some advantages compared to traditional classroom methods (see Section 2.4). By utilising the NST-related expertise and better material resources in out-of-school environments, some of the aforementioned barriers for NST teaching may be circumvented. Moreover, given the educational needs discussed in Chapter 1, informal settings are able to provide a quick response to the growing public interest in NST (for further discussion on the general need for informal education in NST, see Laherto, 2008).

The suggestions put forth here, and in detail in articles **IV** and **V**, strive to help in developing educationally sound out-of-school environments and methods as well as in bringing educational practices and educational research closer together. The suggestions are both presented at a general level and discussed in the context of NST education.

5.4.1 MODEL FOR EXHIBITION DEVELOPMENT

In the theoretical study T3, a model for research-based exhibition development was suggested and then applied in the planning of a nanoscience exhibition. In the suggested approach, presented in detail in article **IV**, the challenge of exhibition development becomes a challenge of creating appropriate *experiences*, related to some aspect of the *target*, that are likely to arouse *reminders in visitors and interact fruitfully with visitors' PAST* (see the terminology in Section 2.4). Each of these elements can be considered in the light of research findings. Such a procedure for employing educational research in the different phases of exhibition development is outlined in Figure 3. The procedure was developed on the foundation of the basic Model of Educational Reconstruction (Duit, 2007, p. 6), and to some extent resembles the earlier practical applications of it (e.g. Duit, Komorek, & Wilbers, 1997).

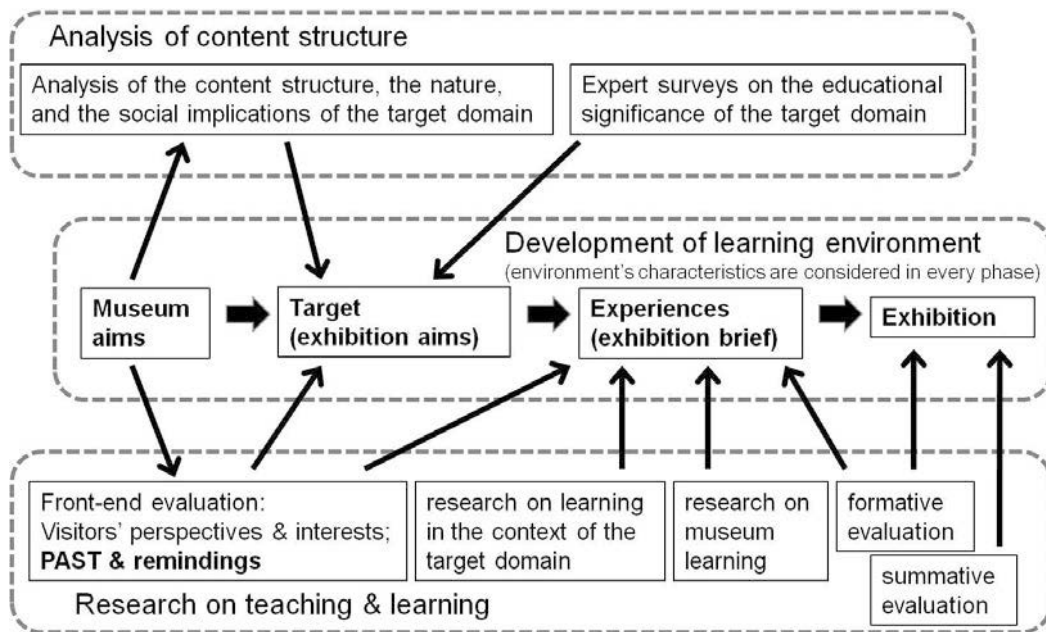


Figure 3 The suggested procedure for informing exhibition development through educational research. Originally published in article IV. Reprinted here by permission of Taylor & Francis.

The development phase of the exhibition planning process (Lord, 2001) can be roughly divided into four steps (Fig. 3): museum aims, exhibition aims, exhibition brief, and the actual exhibition (cf. Grewcock, 2001). The *target* is defined on the basis of the general aims and characteristics of the museum, analysis of the content structure (drawing on literature on the nature and societal aspects of the content, as well as expert surveys) and the front-end **evaluation of potential visitors' typical PASTs and reminders** related to the *target*. The front-end evaluation also guides the development of the exhibition brief, describing the actual exhibits, by identifying fruitful contexts in which the target should be presented. Furthermore, this phase of exhibition development is supported by reviewing the literature on typical challenges in learning the target, as well as general literature on museum learning, in order to find effective means of communication. After the exhibition brief the planning process continues to the design and implementation phases (Lord, 2001), during which the actual exhibition is created and evaluated.

Each of these ways for informing the exhibition development through research is discussed in detail in article IV. In the following, the application of the model to the planning of a prospective NST exhibition is described. In real exhibition projects, museums cannot typically engage in research activities quite as much as in this example. However, their resources may permit at least some of the research-based approaches suggested here.

The process began by considering the general aims of the museum in question (see Fig. 3). On this basis, a tentative set of **'education for citizenship' type aims were set for the prospective exhibition (see article IV)**.

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In focusing these aims, the content structure analysis carried out in study T1 was utilised. According to the suggested model, empirical content-oriented studies may also be used in defining the target of the exhibition (see Fig. 3). The published expert surveys and Delphi studies on the educational significance of NST (Stevens et al., 2009; Wansom et al., 2009) were reviewed, and the results of the teacher survey E1 were also used. All in all, analysis of the content structure for defining the target of the exhibition (Fig. 3) revealed not only the central scientific and technological ideas and concepts of nanoscience and nanotechnology, but also a number of educationally interesting features in the nature of these fields and in their interrelationships with society that are worth addressing in the exhibition.

However, an at least equally important approach in defining the target of the exhibition is front-end evaluation (Fig. 3). The NST exhibition project involved a review of polls and surveys on public perceptions of nanoscience (see e.g. Crone, 2010). However, it is usually also necessary to carry out a local survey of potential visitors to the museum in question. Here, one approach is to survey a statistically meaningful sample of the whole target audience, while another approach is to conduct a small-sample interview or a focus group study in order to gain a deeper insight (although not statistically significant) **into the potential visitors' perspectives. In the nano-exhibition project, the latter approach was chosen (E3).** The results highlighted some fields of nanoscience and nanotechnology that the potential visitors may find especially interesting and relevant.

In the third phase, the exhibition brief (see Fig. 3), findings of the same visitor survey were utilized in order to identify the typical challenges in the learning and communication of NST that must be taken into account when designing the actual exhibits. The exhibition brief was also informed with a review of the educational research literature on the teaching and learning of nanoscience (T2). Educational strategies such as teaching the continuum of scales, using relative comparisons instead of absolute sizes, providing size landmarks and promoting proportional reasoning were also found to be appropriate for exhibitions, and such exhibits were therefore included in the exhibition brief. The findings of T2 and E3 both implied that special attention has to be paid when communicating the nanoscale using STM/AFM images in order to avoid epistemological misconceptions. Furthermore, literature on the learning of nanoscale science highlighted the educational potential of real research instruments such as AFMs (Hingant & Albe, 2010), which are usually unobtainable for schools but perhaps not for museums.

Lastly, the research-based groundwork for the exhibition involved a review of research findings on museum learning (Fig. 3), focusing on reports on previous nanoscience exhibitions. While several exhibitions on this topic have been launched in recent years in museums and science centres all over the world, only a few publications have reported experiences of these projects from an educational viewpoint. When discussing the Brazilian **“NanoAventura” exhibition, Murriello, Contier and Knobel (2009)** stressed

that the most important museographic and communicational challenge in designing exhibits on NST relates to the fact that the objects the fields are based on are invisible to the naked eye. Exactly the same notion is also stated in an **evaluation of “It’s a Nano World”, a travelling exhibition funded by the National Science Foundation in the U.S.** (Batt, Waldron, & Trautmann, 2004). **While “NanoAventura” solved the dilemma of displaying nano-objects in an exhibition by using computer games and virtual representations, “It’s a Nanoworld” employed concrete macroscopic models and analogies.** For the exhibition brief, both types of exhibits were chosen. The literature review increased understanding of the advantages and disadvantages of different museographic approaches, thereby making it possible to use the approaches deliberately.

5.4.2 MODEL FOR INDUSTRY SITE VISITS

The potential of university–school partnerships in teaching contemporary sciences such as nanoscience has been widely recognized. Successful practices of this kind have been reported worldwide (e.g., Sweeney & Seal, 2008), but in Finland no such partnerships focusing on NST-related issues have yet been initiated. On the other hand, Finland has a long tradition of supporting school group visits to enterprises within relevant industries as a part of science and technology education. Moreover, as there are many nanotechnology-related companies in Finland, the suggestion of the respondents (in studies E1 and E2) for students to learn about nanoscience by means of cooperation between schools and related industries appeared a feasible method.

The site visit model suggested in T4 aims to contribute to students’ interest in and attitudes towards science (Osborne, Simon, & Collins, 2003). Scientific literacy is commonly regarded to also involve affective factors. For example, the latest PISA framework (OECD, 2007) provides an expanded interpretation of scientific literacy compared to the earlier frameworks, and also **includes students’ attitudes as an important element of the concept.** Accordingly, the site visit was analysed here mostly from the perspective of student motivation and careers in science and technology.

The site visit model, presented in detail in article **V**, includes the following phases: 1. Advance planning by teachers; 2. Teacher preparatory site visit; 3. Advance preparation with students; 4. Practical preparations for the visit; 5. The site visit; 6. Activities after the visit; 7. Evaluation and feedback with teachers and site representatives; and 8. Collecting ideas for planning future site visits.

The *active learning through reading and writing* methods presented in article **V** support the often-neglected *fundamental sense of scientific literacy*. Norris and Phillips (2003) argued for the importance of this fundamental sense, “reading and writing when the context is science”, while noting that conceptions of scientific literacy generally tend to be connected to

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the derived sense, “being knowledgeable, learned, and educated in science”. They stress that it is not enough to know the meanings of scientific concepts, but to be scientifically literate (in the fundamental sense) one has to understand their interconnections through reading, writing, speaking, listening and representing (Norris & Phillips, 2003). Thereby, in the suggested model the students work as reporters and familiarize themselves with the scientific and technological issues and the professions.

Based on the theoretical problem analysis, features of learning activities that are likely to motivate students in learning during the visit are discussed in article **V. Such activities should support students’ feeling of autonomy, competency and social relatedness** (Deci & Ryan, 2000).

Only some preliminary empirical data were collected in this first design and evaluation cycle. On this basis, as a form of out-of-school education, the site visit model appears to be well suited to enhancing several elements of scientific literacy (cf. Section 2.2): knowledge *about* science, interconnections between science and society (and especially industrial life), and interests in and attitudes towards science. The empirical results indicate that during the visit, students learn mostly about the professions and practical applications, and less about the ‘pure’ science. Students considered the visit as relevant to their interests, which was also essential in the approach to scientific literacy in this dissertation research. The site visit had a positive influence on student motivation to learn science.

6 VALIDITY AND RELIABILITY

This chapter discusses the validity and reliability of the whole study by pulling together the research approaches and methods of all the partial studies. The individual methods were briefly analysed in chapters 4 and 5 and in detail in the articles **I–V**. The reliability of the whole research²⁰ mainly stems from the reliability of the individual instruments used, and to the quality of analysis and argumentation in the individual qualitative studies. Assessing the validity of the whole research requires a scrutiny of the suitability, as well as the strengths and weaknesses, of the chosen multi-method approach in answering the research questions (Cohen & Manion, 1994).

The Model of Educational Reconstruction appears to be a valid methodological frame for analysing an emerging field of science and technology such as NST from a broad educational perspective. The model is, **as discussed in Section 3.2, specifically designed for analysing “whether it is worthwhile and possible to teach particular areas of science”** (Duit, 2007, p. 5). This purpose coheres with the chosen research questions. The validity of MER, however, has not been and cannot be empirically confirmed in a strong sense (see Duit, Gropengiesser, Kattman, Komorek, & Parchmann, forthcoming). As a broad methodological framework, MER allows a wide variety of choices in research methods. Every time the model is employed in a research project, the validity of the study must be considered separately by inspecting how well the research frame and chosen methodology correspond to the nature of the phenomena that was studied and the research questions that were set.

In this study, the wide and explorative nature of the research problem was considered to require multiple methods (see Section 3.3), which is also typical for MER. The dissertation adheres to paradigmatic pragmatism (Brewer & Hunter, 1989), holding that qualitative and quantitative approaches can be mixed in order to answer such explorative research questions. The research objectives were qualitative in nature, but mixed approaches were applied in the course of the research regarding both the type of data and the type of analysis and interpretation. Empirical investigations included a study with qualitative data and qualitative content analysis (E1), a study with quantitative data and statistical analysis (E2), and also a study with qualitative data and quantitative analysis (E3). Furthermore, the theoretical studies T1–T4 increased the diversity of approaches. With such a multi-method approach (mixed-method or mixed-

²⁰ Since the partial studies employ considerably differing methods, comparison of the results determines convergent validity rather than the reliability of the findings (see Brewer & Hunter, 1989, p. 131–132, 137–138).

model research²¹) one can, for instance, generally answer broader research questions, overcome weaknesses of single methods (principle of complementarity), and provide stronger evidence for conclusions through convergence and corroboration of findings (principle of triangulation) (Johnson & Christensen, 2004). However, *exploratory* multimethod studies do not usually place great emphasis on careful insulation of methods to ensure independent cross-validation, but rather focus on exploring a variety of phenomena and viewpoints by using a variety of methods and approaches (Brewer & Hunter, 1989). Accordingly, in this dissertation research the primary rationale behind the multimethod approach was exploration rather than cross-validation. Nevertheless, some triangulation of the results can also be carried out in order to assess the validity of the research.

In order to assess the *convergent validity* (Brewer & Hunter, 1989, pp. 131–132; Cohen & Manion, 1994, p. 281) of the dissertation, several comparisons can be made between methodologically dissimilar partial studies. The results of studies T1 and E1 (reported in articles **I** and **II**, respectively) were compared in Section 5.1. The studies ended up with a quite similar conception of the role of NST in scientific literacy, although the approaches were very dissimilar: T1 approached the problem deductively by analysing literature on the nature of NST and educational goals, whereas E1 **drew inductively on teachers' views**. The two teacher surveys, E1 and E2 (articles **II** and **III**), were also partly comparable, although their focus, sample and methods of analysis differed significantly. As discussed in Section 5.2, conclusions about the possibilities for secondary level NST education are parallel, thereby supporting the validity of the results. Furthermore, the results of the visitor survey E3 match the results of the literature review T2 on the epistemological challenges in using visuals in NST communication (see Section 5.3). The results of all empirical studies E1–3 were coherent not only with one another and with the setting of the study but also with the prior international literature, which further strengthens the validity and credibility of the research (cf. Miles & Huberman, 1994, pp. 278–279).

The convergent validity of the empirical results may, however, be questioned due to the biases in the study samples. As discussed above and in articles **II**, **III** and **IV**, the studies employed *purposeful samples* (Patton, 1990) instead of random samples representative of larger populations. The increase in generalizability due to the use of multiple methods was limited, since teacher surveys E1 and E2, for instance, shared the same source of methodological bias, that is, the respondents in both studies were probably more interested in and aware of NST than an average teacher. This bias affected both studies equally, which does not generally increase the validity of the convergent findings (cf. Brewer & Hunter, 1989, pp. 18–20, 128; Cohen & Manion, 1994, p. 281). Here, however, the bias in sampling was

²¹ The methodology also has features of mixed-model research (Johnson & Christensen, 2004), since different approaches were used not only between partial studies but also within the stages of individual partial studies.

intentional: E1 focused on respondents whose ideas were, to an extent, inspired by the training course content, and E2 sought teachers who are likely to lead the way in incorporating NST into school curricula. The samples were therefore *theoretically relevant* and *representative*, although not *statistically representative* (Brewer & Hunter, 1989, pp. 117–118). Nevertheless, the credibility of conclusions concerning the first research question is admittedly restricted due to the one-sidedness of the research frame. It was beyond the scope of this dissertation research to analyse – or invite the teachers to analyse – the educational significance of NST in comparison to some other fields of science and technology.

The models suggested in studies T3 and T4 cannot be validated in a strong empirical sense, but they need a solid theoretical justification as aspired in articles **IV** and **V**. The usability of the models can be assessed when applied to practice, i.e. planning exhibitions in science centres and museums (T3), and arranging visits to industry sites (T4). The given example on the development of a nanoscience exhibition in article **IV** and the tentative empirical data in article **V** provide starting points for evaluating the practical value of the proposals. Further assessment of the *practical validity* (Patton, 1990) of the suggested models remains to be performed.

The *utilization* of the results, an unavoidable test of the quality of a **study's conclusions** (Miles & Huberman, 1994), is discussed in the concluding chapter. In this dissertation it is argued that the results give rise to implications for the development of the curriculum, instructional materials and out-of-school settings both in Finland and, taking the local setting into consideration, also abroad.

Besides methodological triangulation, the partial studies of the dissertation enable multiple levels of analysis (Cohen & Manion, 1994), i.e. the level of the individual, the group and society. The broadest perspective, that of societal needs and aspects, was to an extent taken in all the articles, **I–V**. Individual perceptions, and their relation to the views of others in the same peer group, were examined in articles **II** and **III** (**teachers' views**), as well as in articles **IV** (**visitors' views**) and **V** (**students' views**). Moreover, the last two articles included an institutional perspective by focusing on the characteristics of science museums (**V**) and industry sites (**IV**) as learning environments. Such a combined-level approach increases the validity and relevance of the conclusions.

7 DISCUSSION AND CONCLUSIONS

This dissertation approached the multifaceted research problem “*What are the educational needs, possibilities and challenges of bringing the topics of NST to schools and out-of-school learning environments?*” from various perspectives: by analysing the connections of NST to scientific literacy; by **surveying science teachers’ perspectives on the educational significance of NST** and the possibilities for arranging instruction in practice; by reviewing the literature on teaching and learning of NST; by surveying science centre visitors; and by forming research-based suggestions for the development of classroom solutions as well as out-of-school learning environments. The research was explorative in nature. In terms of the typology of research objectives presented by Johnson and Christensen (2004), i.e. *exploration – description – explanation – prediction – influence*, most of this research dealt with the first and second aims. The theoretical suggestions for research-based practices presented in articles **IV** and **V** also touch on the aims of *explanation* and *prediction*, but the suggestions remain to be empirically validated. The objective of the study was not directly to *influence*, but to lay the groundwork for the future development of NST education. In this concluding chapter, the results and their potential implications are discussed.

Research question 1, “What is the role of nanoscience and nanotechnology (NST) in scientific literacy?”, was mostly answered in Section 5.1 on the basis of articles **I** and **II**. Despite the “nanohype” (Mitchell, 2007), NST should be considered as an educationally significant field, since it may play a role in responding to the “grand challenges for citizens and societies” (Bybee, 2010). Moreover, it represents all the key features of ‘postmodern science’ that, according to Hurd (1994), should be better addressed in schools to modernise the science curriculum and to “prepare new minds for a new age”. In the context of NST, scientific literacy (as defined in Section 2.2) means abilities such as feeling comfortable and competent with nanoscientific and technological matters and artefacts, following media discussion on NST, and forming informed opinions on personal, social and global issues related to these fields. As argued in Section 5.1 on the basis of theoretical as well as empirical problem analysis, such abilities require an understanding of the implications of NST (including ethical issues, potential benefits and risks, etc.) and a grasp of the nature of this postmodern field (including the interdisciplinarity, the entwined relationship between science and technology, and the interplay between empirical and theoretical research with the distinctive role of modelling, simulations and imaging).

Conceptual knowledge of science content is also an indispensable part of scientific literacy. When selecting and constructing science content for instruction, the **“Big Ideas of Nanoscale Science and Engineering”**²² (Stevens et al., 2009) appear to be a good starting point for Finnish secondary schools as well. The experienced science teachers in study E1 (article **II**), after receiving training on NST content knowledge, pointed out nearly the same **educationally significant issues that were nominated as “Big Ideas” in the U.S. study**. The main difference is that Stevens et al. (2009) focused heavily on scientific principles and processes, addressing applications and **implications only generally in the last “Big Idea”**. The Finnish NST-trained science teachers, on the contrary, emphasised the importance of practical **applications and ethical issues**. **Otherwise, the first four “Big Ideas” (“Size and Scale”, “Structure of Matter”, “Forces and Interactions” and “Quantum Effects”), related to the foundational science content, were explicitly mentioned by the teachers – except for the latter one, as discussed in Section 5.2. The remaining “Big Ideas”, namely “Size-Dependent Properties”, “Self-Assembly”, “Tools and Instrumentation”, “Models and Simulations” and “Science, Technology and Society”, do not directly relate to foundational science content but rather to the phenomena, applications, methods and interrelationships that are specific to NST**. Although they do not have many connections with current curriculum contents, the respondents highlighted every one of these ‘applied’ ideas as being educationally significant. This congruence took place even **though the “Big Ideas” were not presented to the participants at any time during the course, or used when planning the course programme**.

Achieving this level of ‘nano-literacy’ is challenging, however, because of the complexity of the subject matter and the related communicational challenges (see 5.3).

Research question 2, “How do science teachers perceive the possibilities of NST education in secondary schools?”, addressed the barriers and facilitators discussed in Section 2.3. Several groups of experts need to be consulted in the process of curriculum revision, such as education policy makers, scientists and educational researchers (cf. Stevens et al., 2009). This dissertation research, however, focused on the views of science teachers. Their views are certainly worthwhile taking into account, especially given the crucial role of teachers in curricular processes (Clandinin & Connelly, 1992; Kelly, 2004). Research question 2 was answered in Section 5.2 on the basis of the two surveys (E1 and E2) published in articles **II** and **III**.

Despite the international differences in educational systems and national curriculum standards, the Finnish respondents highlighted more or less the

²² The list of “Big Ideas” (Stevens et al., 2009) was compiled by expert consensus for grades 7–9 (lower secondary school), but it essentially coincides with another set of key ideas for grades 10–12 (upper secondary school) that was put together by Wansom et al. (2009).

same barriers hindering NST teaching that have been surfacing worldwide. **The teachers' views on *external* and *internal* barriers** as well as suggestions for ***facilitators*** should be carefully considered when revising the national core curriculum, in planning both preservice and in-service teacher education, and in developing educational materials and methods. An interesting finding was also that only a few teachers in E1 mentioned that secondary level students may have conceptual difficulties in understanding the nanoscale science, i.e. the conceptual complexity was not considered as an additional barrier. A similar finding was presented by Bamberger and Krajcik (2010); their respondents also argued that NST would meet the capacities of this age group.

Moreover, the teachers were surveyed not only regarding the barriers they perceive, but they were also asked to analyse the need for NST education on a more general level (particularly in E1). That is, they were not only asked ***how*** NST could be incorporated into the curriculum, but also ***why*** it should – or should not – be included, and if it should, ***what*** would be the central contents. This approach reflects the relatively deep involvement of teachers in curriculum development processes that is typical for the Finnish educational system (see e.g. Pehkonen et al., 2007). The results are used in the following when answering the final research question.

Research question 3, “*What guidelines does science education research give for the development of NST education in secondary school and in out-of-school settings?*”, demanded multifaceted scrutiny. Answering the question rests on the analysis in connection with the first two research questions (Sections 5.1 and 5.2), the challenges in NST learning and communication analysed in studies T2 and E3 (Section 5.3), and the theoretical work carried out in studies T3–4 (Section 5.4, articles **IV** and **V**). The models suggested for research-based exhibition development (Section 5.4.1 and article **IV**) and arranging industry site visits (Section 5.4.2 and article **V**) provide an answer to the latter part of research question 3, i.e. that concerning out-of-school settings. The former part of the question, concerning the development of secondary school education, is further discussed in the following.

Some curricular issues were already discussed in Sections 5.1 and 5.2. On the basis of both the literature analysis and empirical findings, NST is educationally significant and should be taught at secondary school, focusing on topics specified earlier in this chapter. The surveyed teachers emphasized that NST should be taught as a transdisciplinary theme, a part of science in general, but not at the expense of other content. Thus, different strategies of incorporating the topics of NST into the existing subject curricula must be elaborated.

It may be argued that NST even offers an opportunity to teach all science in a novel way. Traditional science education research and research-inspired instructional approaches are focused on separately teaching and learning

specific topics in school curricula, one at a time. Nanoscience, however, entails an integrative view of all science. It deals with the behaviour of materials and devices as a combination of the atomic and bulk properties, and in this approach several core concepts of a number of school sciences need to be simultaneously processed. Teacher professional development on nanoscience and the development of teaching and learning materials should, as argued in article **III**, concentrate on using the scale and the “Big Ideas” as tools for unifying the existing school science, rather than on including additional modules in the curriculum.

Such an integrative approach seems to fit especially well into the teaching of the fundamental scientific concepts that NST is based on, i.e. the first four **“Big Ideas”**, since they are already discussed to some degree in the secondary level curriculum, as noted above. Incorporating the applications of NST into the curriculum, as emphasized by the respondents in E1, may be more challenging due to the curricular limitations. On the basis of the survey results, it thus seems that the essential issues of NST do not fit into the curriculum just by adding them, but rather would require a more thorough curriculum revision. Accordingly, in the recent literature on science education policies, NST has even been proposed as the route to a new kind of interdisciplinary curriculum (Stevens et al., 2009) or a **“catalyst for educational reform”** (Schank, Krajcik, & Yunker, 2007). Stevens et al. (2009) **advocate coherence in the science curriculum and suggest the “Big Ideas” of NST as its foundation** – although admitting that in practice achieving this kind of fundamentally interdisciplinary NST **teaching is “more complex than simply adding NSE examples into current lessons or inserting an NSE module into the current curriculum”** (Stevens et al. 2009, p. ix).

There are also easier approaches for bringing NST to school. To begin with, a curriculum including comparisons of phenomena through different scales would address many of the NST-related educational concerns discussed in this dissertation. Teachers in study E1 (article **II**) suggested that the easiest way to introduce NST at the secondary level is as an optional course in upper secondary school. Since the respondents in both teacher surveys agreed that general education in nanoscience should be provided, and that at the time it is difficult to accomplish its integration in schools, the findings also motivate the search for alternatives to classroom teaching. The teachers perceived that both types of barriers – intrinsic and extrinsic – can be sidestepped by using out-of-school learning environments and inviting nanoscientists to science lessons. Such a ‘lightweight’ introduction to nanosciences could serve as the starting point for nationwide, school-based NST education. This dissertation suggested two approaches for the development of out-of-school settings. As science teachers ultimately become responsible for teaching more nanoscience content by themselves, they will need strong support from the nanoscience and education research communities in the form of material resources and professional development.

Finally, it is worth noting that quite many of the results of this dissertation are somewhat similar to those of the aforementioned U.S. studies on the **educationally important aspects as well as teachers' barriers related to NST**. However, the meaning of the study is still more than confirmatory. Curriculum development always requires locally laid groundwork, and the teachers who are implementing curriculum innovation must be heard in the first place (cf. Anderson & Helms, 2001; Peers et al., 2003; van Driel et al., 2001). Previous studies of this type have all been carried out within the U.S. educational system, which is somewhat different from the Finnish one.

Further research on the complexities of NST education is needed. This dissertation research was only able to perform the exploratory groundwork and map the terrain for the various opportunities and challenges for NST education and scientific literacy. The next logical steps could at least include the development of modules for teaching and learning that address the concerns and challenges pointed out here, and evaluation of how those solutions work and reach the goals. Likewise, the development of out-of-school settings according to the research-based suggestions presented here, and evaluation of **the learning outcomes and learners' experiences would be** helpful both in validating the suggested models and – hopefully – in enhancing the needed nano-literacy.

As this dissertation research applied the Model of Educational Reconstruction in a somewhat untypical manner, some methodological conclusions may be drawn. Most of the earlier applications, discussed in Section 3.2, have focused on the development of teaching–learning sequences and involved iterative evaluation and improvement of such practices. However, the model also appears to suit explorative studies such as this dissertation research. Whether the aim is to map the need and possibilities of education in a novel field or to develop a specific educational practice, the MER provides a useful framework that is general and flexible enough. Furthermore, the model was here extended to settings for informal and out-of-school learning. The basic structure of the model, i.e. the three components and their close interplay, serves the general purposes of studying and developing environments such as museum exhibitions. However, as the MER does not explicitly take into account the broader educational context, the model has to be specified with a view of learning in settings other than schools. Such adaptation was suggested in this dissertation.

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APPENDIX A: QUESTIONS OF THE INTERVIEW STUDY

Translated from Finnish by the author

1. Have you heard or read about nanoscience or nanotechnology (NST)?
2. From where have you heard/read about NST?
3. Have you studied NST, or has your work experience concerned these fields?
4. In your opinion, what fields of science is NST related to?
5. In your opinion, what does NST mean?

When the respondent has responded to question 5, the interviewer provides a simple definition of NST: “Nanoscience and nanotechnology concern the research, manipulation and construction of very small structures. According to a common definition, the structures of NST are in the size range of 1–100 nanometres, at least in one dimension (length, breadth or thickness). A nanometre is one millionth of a millimetre. This means that the structures of NST can be as small as a few molecules or atoms. At this scale, matter gains new properties that depend on size. These properties can, for instance, be mechanical, electrical or optical.”

6. Do you know some applications or products that exploit nanotechnology?

7. Here I have talked about nanoscience and nanotechnology. Do you think that there is a difference between them?

The interviewer shows an STM image of a nanoscale structure. [“Quantum corral”, image originally created by IBM Corporation and available at the STM Gallery, <http://www.almaden.ibm.com/vis/stm/gallery.html>. The image is also on the cover of the printed version of this dissertation.]

8. What do you think is presented in this image?

After the respondent has answered question 8, the interviewer tells that there is a copper surface, in which a ring is constructed out of single iron atoms. The diameter of the ring is ca. 7 nm.

9. How and with which instruments was this image created?

The interviewer tells that the image was created with a scanning tunneling microscope. STM has a sharp tip that is slowly moved across the surface, measuring the properties of the surface.

10. On the basis of this image, what can you say about the iron atoms or the copper surface?

11. For what purpose do you think images of this kind can be used in nanoscience?

The interviewer shows a computer simulation and gives the following explanation: “In this computer simulation a small, spherical carbon structure collides with a tubular carbon structure.”

12. When you think of the creation of this video and the recent image, what similarities and differences come to your mind?

After the respondent has answered question 12, the interviewer explains: “The carbon nanotube shown in the video is one important structure studied and applied in NST. It has interesting properties: a carbon nanotube is extremely strong and it conducts electricity and heat very well. It is a good example of a central idea of NST: below a certain size, matter may exhibit totally new and even revolutionary properties.”

13. What do you think these new properties result from?

14. Generally speaking, what potential benefits do you think will follow from nanotechnology?

15. What disadvantages and risks will follow from nanotechnology?

16. Which do you consider more significant, the benefits or the disadvantages/risks?

After the respondent has answered question 16, the interviewer says: “Finally, I will read some statements. Please respond on the scale 1...5 depending on how much do you agree with the statement. ‘1’ means you do not agree at all, and ‘5’ means you completely agree. You can also respond ‘I cannot say’.”

17. The general public should be heard when making decision on the development of NST.

18. Decisions on NST should be made on the basis of expert views and advice.

19. Decisions on NST should be made on the basis of views of average citizens.

20. Decisions on NST should be based on scientific knowledge of the risks and benefits.

21. Decisions on NST should be based on moral and ethical considerations.

22. Citizens should be told about NST and be able to decide independently, whether they want to use products developed with these methods.

23. Although nanotechnology may bear some unknown risks, it is inevitably part of our future, so we should just make sure that it is used as safely as possible.

24. NST should be regulated and supervised more strictly than before.

25. I am interested in knowing more about NST.

26. What about NST interests you the most?