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Mikko Kesonen

Improving students' learning about optics at university

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UNIVERSITY OF
EASTERN FINLAND

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ABSTRACT

The present dissertation provides an overview of a study that has aimed at improving university students' learning of optics. In the dissertation, the study is divided into three sub-studies that cover students' learning of optics from different perspectives.

The first sub-study focuses on students' understanding of the electromagnetic nature of light. It shows that instructed students often face a difficulty in applying the interrelations of the electric and magnetic fields in various contexts, including light. This result indicates a need to develop an instruction targeting to improve students' understanding of the interrelations of the electric and magnetic fields. To develop such instruction, the findings of sub-study 1 provide a useful starting point.

The second sub-study covers the adoption of the Tutorials in Introductory Physics curriculum. The study introduces the tutorial intervention, that is, a fairly easy way to use the curriculum in a lecture hall setting. In addition, sub-study 2 provides evidence according to which the intervention improves students' learning of optics. Thus, it is argued that the tutorial intervention can be included as a useful supplement in a conventional lecture-based physics course.

The third sub-study focuses on the context dependency of students' reasoning with regard to optics. It demonstrates how explicitly labelled light sources in optics task assignments may impact on students' reasoning regarding optics. Students' reasoning was found to correspond to the perceptible features of the light sources explicitly stated in optics task assignments. This type of student reasoning was often found to be inconsistent with the subject matter of optics, thus hindering students' learning of optics. To explain why students' reasoning corresponded to the perceptible features of the light sources, the Johnson-Laird mental model theory was adopted. When read through this theory, it seems obvious that the light sources trigger certain types of mental representations on the part of students. These representations mimic perceptible features of the

light sources rather than their underlying subject matter of optics. The representations may explain why students' reasoning was found to correspond to perceptible features of the light sources rather than to the desired subject matter of optics. Finally, sub-study 3 demonstrates that the Johnson-Laird mental model theory is applicable in explaining the context dependency of students' reasoning of optics. We would contend that the theory would also be useful in explaining the context dependency of students' reasoning of physics in general.

All three sub-studies were conducted in the course of 2009-2013 at the Department of Physics and Mathematics of the University of Eastern Finland. Both qualitative and quantitative data-gathering and -analysis methods have been employed by following the mixed methods study approach. The principles of content analysis research are applied in the analysis of students' responses.

Overall, the findings of the present study can be used to improve students' learning of optics more globally than in the study context within which this study has been implemented. Thus, the findings of the present study provide a good starting point for the development of optics instruction.

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Preface

I'm grateful to have been given the opportunity to carry out this study. It would not have been possible without financial support provided by the Finnish Optical Society, the Finnish Cultural Foundation, the Physics Education Research Leadership Organizing Council, and the Department of Physics and Mathematics at the University of Eastern Finland. My thanks go to all of these organisations for making this possible.

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I also wish to thank the staff, colleagues, and friends at the Department of Physics and Mathematics. Seeing you during lunch or café breaks has been the greatest moment of many, if not all, of my days in office. Special thanks to Risto Leinonen and Ville Nivalainen for sharing an office with me; your jokes, support, and comments have always been thoroughly appreciated.

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Joensuu, 29 August 2014 *Mikko Kesonen*

LIST OF PUBLICATIONS

This thesis is based on data presented in the following articles, referred to by the Roman numerals I-IV.

I Kesonen, M., Asikainen, M. A., and Hirvonen, P. E. (2011). University students' conceptions of the electric and magnetic fields and their interrelationships. *European Journal of Physics*, *32*, 521-534. (Reprinted with the kind permission of IOP)

II Kesonen, M., Asikainen, M. A., and Hirvonen, P. E. (2012). University students' difficulties in a tutorial featuring two source interference. In A. Lindell, A.-L. Kähkönen, & J. Viiri (Eds.), *Physics Alive. Proceedings of the GIREP-EPEC 2011 Conference, (pp. 74-79). Jyväskylä: University of Jyväskylä.* (Reprinted with the kind permission of the editors)

III Kesonen, M., Asikainen, M. A., and Hirvonen, P. E. (2013). Assessing the impact of a tutorial intervention when teaching the ray model of light in introductory physics. *European Journal of Physics*, *34*, 849-857. (Reprinted with the kind permission of IOP)

IV Kesonen, M., Asikainen, M. A., and Hirvonen, P. E. (submitted). Hybrid models of light triggered by different light sources. Submitted to the *Physical Review Special Topics – Physics Education Research* and considered as a publication with major revisions. (Reprinted with the kind permission of APS)

AUTHOR'S CONTRIBUTION

The author has established the theoretical background used in articles I-IV together with his supervisors. Regarding the design of the data-gathering methods, the author had the main responsibility in articles I-IV. The author has had the sole responsibility for gathering the data for article I and in part also for articles II-IV. The author designed the tutorial intervention mainly by himself and implemented it with the assistance of his supervisors. The author has taken care of the analysis of the results presented in articles I-IV. Finally, the author has borne the main responsibility in writing articles I-IV.

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1 Introduction

Optics, the study of light, is a challenging subject to learn. To confront the challenge that it poses, I have undertaken an extensive study, which is summarized in this dissertation. Much of this study has already been published in articles I-IV, but this dissertation supplements these articles by describing their background in greater detail.

The following chapter introduces the research field which it is hoped that the present study contributes to. It also clarifies the purpose of this study with a brief description of its underlying research process. Finally, this chapter also outlines the structure of this dissertation as a whole.

1.1 TARGETING THE PER FIELD

The present study has aimed at contributing to the field of *Physics Education Research* (PER). This is a subfield of physics whose members – typically physicists – treat students' learning of physics as a scientific problem (Redish & Steinberg, 1999; Beichner et al., 1995). In the past, physicists have compromised the "scientificness" of this problem by arguing that teaching is more an art than a science (McDermott, 2001). Despite this inborn scepticism, since the 1970s a growing number of people have recognised PER as scientific enterprise (Cummings, 2011). Today, PER is a worldwide research field[1], and its findings have been widely used in physics education, especially at university level in the United States (Henderson & Dancy, 2009; Heron & Meltzer, 2005).

[1]International PER organizations: PER central (http://www.compadre.org/per/); GIPER (http://www.girep.org/); ICPE (http://web.phys.ksu.edu/ICPE/index_nf.html)

1.1.1 A peek at the history of PER

What PER is today has largely arisen from teachers' and professors' concern that students do not learn physics as well as might be expected. In the United States, this concern grew in the middle years of the 20th century, when the subject of physics was treated as a "gatekeeper" for students who had what it takes. (Cummings, 2011) After 4 October 1957, when the Soviet Union launched the world's first satellite, *Sputnik I*, into space, the government of the USA suddenly had numerous reasons to invest in a reform of science education in order to catch up with the USSR in the science and technology race (Wissehr & Concannon, 2011). As part of this race, an increasing amount of resources became available to teachers and professors for them to focus on improving physics education (Cummings, 2011). After some mismatched improvements, such as physics textbooks that proved too demanding for upper secondary schools, it became evident that simply enhancing the presentations of physics was inadequate for improving students' learning (McDermott, 1991). This highlighted the need to approach students' learning more systematically, in the same way as physicists had approached nature while discovering its behaviour (McDermott, 2001; Hestenes, 1999; Reif, 1995). Introducing this discipline-based research approach into the practice of physics education led to the emergence in the 1970s of PER in the United States (Beichner, 2009). The first PER research group was organized at the University of Washington (Cummings, 2011), where the first PhD degree concerned with the teaching and learning of physics was also awarded (Kalman, 2008). Today, PER regards itself as *discipline-based educational research* (Redish, 2014; McDermott, 2001) whose ultimate goal has remained the same as it was originally – to improve students' learning of physics.

1.1.2 Steps taken in PER

During the history of PER, the goal of improving students' learning of physics has been approached in a variety of ways. The early stages of PER mainly involved the identification of difficulties encountered by students in the learning of basic top-

ics in introductory physics (see, e.g., (Goldberg & McDermott, 1986; Clement, 1982; Trowbridge & McDermott, 1980)[2]. The student difficulties identified created a basis for more sophisticated PER contributions, such as research-validated conceptual surveys (Redish, 2003; Hestenes, 1999). These surveys revealed how common particular student difficulties were across different student populations and educational cultures (Kim & Pak, 2002; Viiri, 1996). In addition, the surveys provided fairly reliable measurements that indicated students' learning in various instructional settings via pre- and post-testing procedures. This line of research has broadly demonstrated that conventional lecture-based physics instruction is an ineffective method of supporting students' conceptual understanding of physics (Maloney, O'Kuma, Hieggelke, & Van Heuvelen, 2001; Hallounn & Hestenes, 1985). Thus, for the majority of students, following physics lectures merely by listening and by solving quantitative chapter-end problems is found to be inadequate for creating an expert-like understanding of physics[3]. To sum up, the conceptual surveys broadened awareness of students' conceptual difficulties. This increased awareness gave extra impetus for a different type of PER that went beyond documenting students' errors and interpreting their causes.

This type of PER aims at developing instructional practices that would improve students' conceptual understanding of physics (Reif, 1995; Van Heuvelen, 1991). Nowadays, various research-based instructional practices have been developed by relying on systematic research into students' learning (Redish, 2003; Crouch & Mazur, 2001; McDermott, 2001)[4]. Many of these research-based practices may be characterized with the terms *interactive-engagement* (Hake, 1998) and/or *active learning* (Meltzer

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[2] For a more comprehensive list of PER studies identifying student difficulties, see (McDermott & Redish, 1999).

[3] This type of understanding typically refers to the ability of students to apply their physics knowledge successfully in unfamiliar situations involving qualitative reasoning.

[4] Some modern instructions are based on extensive teaching experience rather than systematic research, see e.g. (Knight, 2002).

& Thornton, 2012). In concrete terms, they refer to an instructional style in which students are asked to reflect several times during a lesson on their ideas about the subject matter being taught; they are guided through carefully developed tasks being taught by questioning rather than telling; and the student learning is monitored frequently in order to evaluate the effectiveness of a given instruction and to reveal where there may be a need for further improvements. This type of teaching has been found to improve students' conceptual understanding of physics better than conventional lecture courses. However, this type of teaching also requires more resources than are typically available for a conventional lecture-based physics course. In the present study, we have dealt with this problem by adopting a research-based instructional curriculum called *Tutorials in Introductory Physics* (McDermott et al., 2010a).

1.1.3 More empirically driven research

PER as described above has approached students' learning of physics primarily in an empirical manner. This does not mean that such PER studies have been conducted with no theoretical stance. On the contrary, their stance has provided, for example, a detail criterion for what counts as an adequate student understanding of a physics phenomenon under investigation in a particular instructional context. This stance, however, has offered few insights into the origins of students' answers and their behaviour in various instructional settings. In order to understand students' learning more comprehensively, some PER researchers have highlighted the need to develop the theoretical framework of PER. For example, Redish (2012) has argued that PER – like any science – requires three supplementary approaches, *experiment*, *engineering*, and *theory*, which will permit the construction of scientific knowledge related to its target. PER has a strong tradition of identifying student difficulties – conducting experiments – and of developing physics instructions – engineering teaching – but an approach based on theory has largely been omitted (Redish, 2014). Existing theories of learning, such as constructivism (Bransford, Brown, & Cocking, 2004), have been

acknowledged as a necessary base for the development of the theory of PER, but they are treated as inadequate by themselves (Redish, 1999). Nowadays, a *resource-based framework* of student reasoning (Hammer, Elby, Scherr, & Redish, 2005; Hammer, 2000) represents one of the most developed theory-based approaches used in the field of PER. In the present dissertation, the framework is discussed in greater detail in chapter 3.

1.1.4 PER and other fields of educational research

Despite PER's diverse interest in students' learning, it has obviously distinguished itself from traditional educational research (Redish, 2012; McDermott, 2001). This distinction has arisen from PER members' background. They are typically experts in physics looking at students' learning from a physics perspective rather than from an educationalist's viewpoint (Heron & Meltzer, 2005). This perspective has focused on students' learning of physics content rather than debating research methodologies that are considered valuable in the educational sciences.

In addition, PER differs somewhat from a closely related field known as Science Education. The difference is that PER is a subfield of physics, whereas Science Education establishes itself as *a discipline sui generis* (Dahncke, Duit, Östman, Psillos, & Puskin, 2001). This means that Science Education is not a subfield of any "mother" discipline of science but stands as a discipline of its own (Duit, Niedderer, & Schecker, 2007).

Despite this difference between PER and Science Education, it would not be practicable to draw a clear-cut distinguishing line between them. In consequence, the present study treats these fields as complementary sources of information. The reason why the present study has focused solely on the field of PER is based on practicality rather than principle. At the start of this study, the literature dealing with PER offered more concrete ways of attempting to improve students' learning of optics, and hence the study has shifted towards PER rather than Science Education.

1.2 AIMS OF THE PRESENT STUDY

The present study has aimed at improving students' learning of optics at university. Optics is defined as the study of light that explains the behaviour of light in terms of electromagnetic waves[5] (Photonics Dictionary, 2014). We have approached students' learning of optics by

- exploring their understanding of the electromagnetic nature of light (article I);
- evaluating the impact of tutorials on students' learning of optics when these tutorials were implemented in lecture hall (articles II & III); and
- exploring the role played in students' reasoning of optics by explicitly labelled light sources in optics task assignments (article IV).

As these approaches imply, we have considered students' learning of optics from a variety of perspectives. The selection of these perspectives was undertaken alongside the research process described in section 1.3, below.

1.3 RESEARCH PROCESS

When the present study was started in the Autumn of 2009, its original purpose, as article I suggests, was to improve students' understanding of the electromagnetic nature of light. This seemed reasonable since earlier studies indicated that students may encounter serious difficulties in learning about the electromagnetic nature of light (Ambrose, Heron, Vokos, & McDermott, 1999). The present study was intended to develop an instructional artefact that would support students' learning about the electromagnetic nature of light. As a first step, we took advantage of a data set that I had collected for my Master's thesis in 2008. The data set revealed that students receiving instruction

[5] For a more comprehensive discussion, see chapter 2.

were often unable to recognize the interrelations between the electric and magnetic fields in a variety of contexts. This finding was reported in article I. One of the purposes of the article was to rationalize the relevance of focusing on students' learning about the electromagnetic nature of light.

As the study proceeded, we realized that students also faced problems in the more elementary topics of the ray model and the wave model of light than they did with the electromagnetic nature of light. This realization became evident from the teaching experiences that I obtained at the start of this study while working as a part-time teacher at the Department of Physics and Mathematics of the University of Eastern Finland. The problems also became evident from the research literature concerning the teaching and learning of optics[6]. It seemed that students may be unable to improve their understanding of the electromagnetic nature of light if they do not understand the basics of the ray model and the wave model of light. Thus, the research scope of the present study was shifted onto the basics of the ray model and wave model of light.

After shifting the scope of the research, we decided to make use of existing research-based instructional practices, namely the Tutorials in Introductory Physics (tutorials) -curriculum developed by the Physics Education Group at the University of Washington. Our adoption of the tutorials was motivated by what we considered to be plausible research evidence showing their effectiveness in improving students' understanding of the basics of the ray model and wave model of light (Wosilait, Heron, Shaffer, & McDermott, 1999; Wosilait, Heron, Shaffer, & McDermott, 1998). In order to understand the actual use of the tutorials, I spent the Autumn semester of 2010 with the Physics Education Group (PEG) at the University of Washington (UW).

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[6] One of the results of the literature review made at the beginning of this study was that we were able to establish a webpage that was intended to inform Finnish teachers about the most frequent difficulties encountered by students' in learning optics: https://www.uef.fi/fi/fysopet/optiikan-oppimisen-ongelmat (Kesonen, Asikainen, Kuittinen, & Hirvonen, 2010).

During the semester, I worked as a teaching assistant at the authentic tutorial sessions; I familiarised myself with the context of the tutorials by studying the *Physics by Inquire* curriculum. In addition, I participated in the weekly formal and informal meetings that were held by the members of PEG UW. Spending the semester in this way provided me with a comprehensive understanding of how to adapt the tutorials for use at the Department of Physics and Mathematics at University of Eastern Finland (UEF). These skills were put to good use during the Spring semester of 2011, when two tutorials were tested for the first time at the Department of Physics and Mathematics at the UEF. These tutorials have now been used for four consecutive years (2011-2014), and the research data on students' learning that we obtained is presented in articles II and III and in this dissertation.

In parallel with the adoption of the tutorials, we decided to investigate the extent to which the light sources used in optics task assignments impact on students' reasoning. This undertaking was motivated by findings obtained from a small-scale study in which I was involved while still visiting at PEG UW. As part of that research, I was able to assess students' responses to test questions which happened to have different but explicitly indicated light sources. Some of the students' responses indicated that their reasoning focused more on the properties of these light sources than on the actual subject matter of optics. Since earlier PER studies had not then dealt with the role played by different light sources on student reasoning with respect to optics, we decided to focus on this as an additional part of the present study.

However, this part of our research, proved to be difficult due to a lack of reliable test questions and the absence of student volunteers to participate in the necessary interviews. These shortages created some uncertainty about the meaning of our empirical findings. I had the opportunity to raise these concerns at the World Conference on Physics Education in the Summer of 2012 (Kesonen, Asikainen, & Hirvonen, 2012). Following my talk, members of the audience encouraged me to look more closely at the context dependency of the students' reasoning.

This turned out to be a valuable suggestion since it permitted us to rationalize much of the data collected in 2011-2013. With the aid of this data, we were then able to develop a fresh perspective on earlier PER contributions regarding students' reasoning of optics. These findings are presented in article IV, which represents our best attempt to capture the complex phenomenon of students' learning of optics.

To sum up, the present study has followed an interest-driven research path. During this process, the research scopes have undergone refinement as our understanding of students' learning of optics has developed. As a consequence, the research topics covered in articles I-IV vary, capturing different perspectives on students' learning of optics. Despite the degree of variation, I would argue that articles I-IV comprise a single study that provides useful information concerning the improvement of students' learning about optics. The rest of the dissertation is devoted to justifying this argument. I shall begin my argumentation by clarifying the research topics covered in articles I-IV.

1.4 SUB-STUDIES 1-3

The topics covered in articles I-IV are best understood as individual sub-studies, which are labelled as follows:

1. *Students' understanding of the electromagnetic nature of light (presented in the article I)*
2. *Evaluating students' learning when they worked with the tutorials tasks covering the basics of the ray model and the wave model of light in a lecture hall setting (presented in the articles II and III)*
3. *Understanding the role of different light sources in students' reasoning of optics (presented in the article IV)*

These sub-studies are individual in the sense that they have each covered different topics related to optics; they have employed different data sets aimed at responding to different research questions; and, thirdly, they have aimed at contributing

to the various debates conducted in the PER literature. In consequence, the research topics discussed in this dissertation and in articles I-IV are from now on treated as sub-studies 1-3, as mentioned above.

The presentation of these sub-studies is divided into seven chapters. Chapter 2 introduces the subject matter of optics essentially covered in sub-studies 1-3. Chapter 3 presents the vocabulary used to conceptualize students' learning. Chapter 4 outlines the study context and methodological approach that we have used in the present study. Chapters 5-7 provide an overview of each sub-study, clarifying their backgrounds, implementations, and results. Chapter 8 closes this dissertation by reflecting on the implementation of the study and discussing its relevance.

2 The ray model and wave model of light

Light is a complex entity to grasp, as has been shown by the historical development of optics. Its complexity has permitted the unification of theories of physics, as the integration of electromagnetism and optics shows. The complexity of light has also supported the discovery of quantum physics and wave-particle dualism that exist at a level beyond the intuition of the human mind. (Hecht, 2002) Due to the complexity of light, the theory that explains its behaviour needs to be simplified when it is taught at the certain level of education. The present chapter will discuss these simplifications while covering the subject matter of optics that has been relevant for the sub-studies 1-3. The sections 2.1 and 2.2 start this discussion by presenting an overview about what light is conceived to be in optics. The rest of the chapter focuses on how optics is taught at the introductory level of the university studies.

2.1 A DESCRIPTION OF LIGHT

Light is a visible part of the electromagnetic spectrum. In optics, the behaviour of this part is described in terms of waves whose wavelength varies between approximately 400-700 nm (Dereniak & Deneniak, 2008)[7]. These waves convey the electro-

[7] The particle nature of light is often omitted from the definition of optics and included instead in the study of photonics (Photonics Dictionary, 2014). In addition to light, optics covers the behaviour of ultraviolet (10 nm – 400 nm) and infrared radiation (700 nm – 1 mm). These three regions of electromagnetic spectrum are together known as the *optical spectrum*. (Pedrotti & Pedrotti, 1998)

magnetic energy while oscillating in time-harmonic fashion perpendicularly to the direction of their propagation (Hecht, 2002; Saleh & Teich, 1991). This type of oscillation is similar what can be observed in the context of mechanical waves. As a consequence, the behaviour of light is often paralleled with the behaviour of mechanical waves, such as water waves in a ripple tank. This will be presented later in this chapter.

In contrast to mechanical waves, light may propagate in the empty space where it travels at the speed of light (c). The interaction between material and light is mainly captured in terms of the refraction index (n) of a material. This index can be determined with the aid of a formula,

$$n = \frac{c}{v}, \tag{2.1}$$

where v is the speed of light in a transparent material.

In the field of optics, the electromagnetic theory of light provides the most complete description of light. The theory shows that the behaviour of light is best understood in terms of electromagnetic waves. These waves consist of the electric and magnetic field vectors ($\boldsymbol{E}, \boldsymbol{B}$) that oscillate independently of their source – electric charges. Below are presented Ampere-Maxwell and Faraday laws, which together provide the theoretical foundation defining the existence of these waves in free space.

$$\oint \boldsymbol{B} \cdot d\boldsymbol{s} = \epsilon_0 \mu_0 \frac{d}{dt}\left(\int \boldsymbol{E} \cdot d\boldsymbol{A}\right), \tag{2.2}$$

$$\oint \boldsymbol{E} \cdot d\boldsymbol{s} = -\frac{d}{dt}\left(\int \boldsymbol{B} \cdot d\boldsymbol{A}\right). \tag{2.3}$$

These laws essentially show that an electromagnetic field may exist independently of electric charges by showing that a changing electric field induces a changing magnetic field, and *vice versa*. Changes of this type occur in the context of the time (and space) harmonic electromagnetic plane wave, where the electric and magnetic fields oscillate perpendicularly to each other and in the direction of the wave propagation, as illustrated in Figure 2.1. In the field of optics, the electromagnetic plane wave is one

of the most accurate descriptions of light[8]; it explains the behaviour of light in various optical phenomena, such as in the context of a (linear) polarizer. The polarizer itself is an optical component that filters light according to the oscillating direction of the electric field (Hecht, 2002). At the introductory and intermediate levels of university studies, the working principle of a polarizer is typically explained in terms of a wire-grid polarizer (Knight, 2008a; Young & Freedman, 2004; Hecht, 2002). The polarizer is assumed to consist of parallel conducting wires. The energy of an electric field is absorbed by these wires whenever any of its vector components is parallel to them. An extreme case occurs when the electric field oscillates completely parallel to the wires. In this situation, the wires absorb the energy of the electric field completely, and the electric field stops at the polarizer. Due to the interrelations of electric and magnetic fields, the magnetic field cannot maintain its oscillation without a changing electric field, and hence it will also stop at the polarizer. This explains why linearly polarized light does not pass through a polarizer when its transmission axis is perpendicular (i.e., the electric field is parallel to the wires) in the direction of the incoming electric field.

Students' understanding of the aforementioned electromagnetic nature of light was investigated in sub-study 1. Sub-studies 2 and 3 focused on students' understanding of the ray and wave descriptions of light. The following section discusses how these descriptions are related in optics.

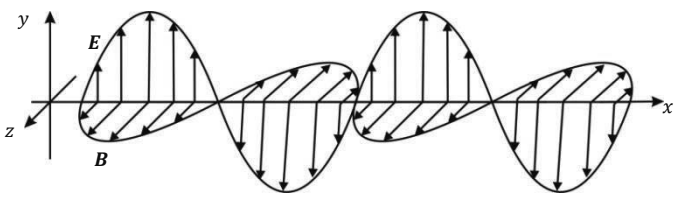


Figure 2.1. *The electromagnetic plane wave model of light takes the electromagnetic nature of light into account (modified from* (Hecht, 2002)).

[8] To model a real beam of light, the superposition of these waves is needed to form the angular spectrum presentation of the beam (Saleh & Teich, 1991).

2.2 THE WAVE AND RAY DESCRIPTIONS OF LIGHT

In circumstances where the wavelength of light is infinitesimally small compared to the details of an optical system, light can be treated as *rays* (Saleh & Teich, 1991). The rays are infinitely thin lines that indicate the direction of the wave propagation from a light source (Dereniak & Deneniak, 2008). Figure 2.2 illustrates the relationship between the rays and waves in the context of a monochromatic point source of light. The rays are another way of describing the path taken by the electromagnetic energy of light. This path is perpendicular to the wavefronts, as illustrated in Figure 2.2. In contrast to waves, rays do not carry information about the phase of light, and hence they cannot interact (interfere) with each other. In an isotropic and homogenous medium[9], light rays travel rectilinearly. This makes it possible to describe the behaviour of light with the aid of straight arrows. (Dereniak & Deneniak, 2008) In many cases, these arrows are an easier way to illustrate the behaviour of light than drawing the wavefronts. Thus, the concept of a light ray has a great practical value in optics, although it is an approximate description of light.

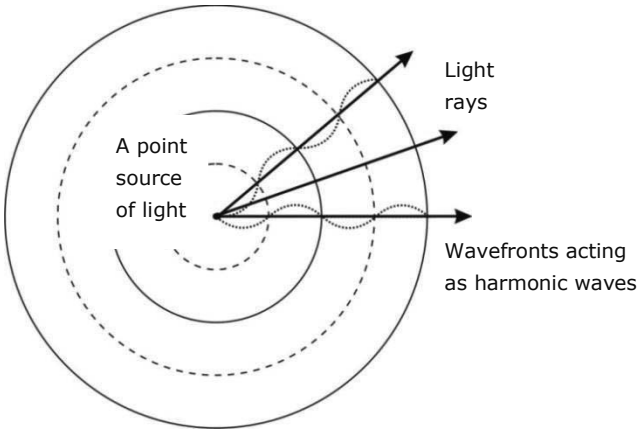


***Figure* 2.2.** *Waves and rays emerging from a point source of light (modified from* (Dereniak & Deneniak, 2008))

[9] In an isotropic medium, the refraction index is independent of the direction of light; the structure of the homogenous medium is considered to be uniform (Photonics Dictionary, 2014).

Section 2.3 that follows illustrates how the ray and wave descriptions of light have been taught in the context of the present study.

2.3 TEACHING OPTICS

At the introductory level of university studies, optics is typically taught in terms of *conceptual models* (Greca & Moreira, 2000) which simplify the accepted theory of light. In these models the impact of a few eccentric quantities (e.g., the coherence properties of light) on the behaviour of light is ignored. These simplifications are intended to make the subject matter of optics more understandable to students and thus may support their learning (see, e.g., (Knight, 2008b)).

In the course of the present study, the use of conceptual models became evident to us when we made use of a textbook by Knight (2008a). The textbook argues that light rays and waves are best conceptualised as two distinct models of light, rather than as different ways of describing the route followed by electromagnetic energy. These models are termed the *ray model* and the *wave model of light*. They are presented as distinct models in the sense that they each possess a certain validity range according to which equations associated with these models are valid and applicable (Knight, 2008a; 2008b). In addition, the textbook provides an explicit rule where the validity range of the ray model ends and that of the wave model starts, as shown in section 2.5. Sections 2.3 and 2.4 discuss the wave model and ray model of light, respectively, covering the subject matter of optics that was relevant the sub-study 2.

2.4 THE WAVE MODEL OF LIGHT AND THE PHENOMENON OF TWO SOURCE INTERFERENCE

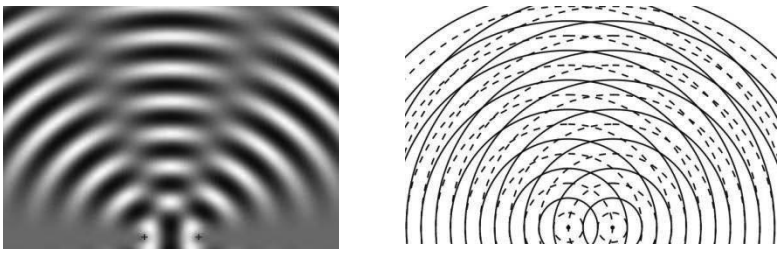
As mentioned in section 2.1, in the field of optics light is considered to behave in the form of waves. At the introductory level of

university studies, the wave nature of light is typically emphasised in the context of inference and of the diffraction phenomena of light, for example, when covering Young's double-slit experiment (Knight, 2008a; Young & Freedman, 2004). In this particular experiment, light passes through two narrow slits, creating the appearance of dark and bright interference fringes on a distant screen. The experiment is easiest to perform using monochromatic and coherent light sources such as a helium-neon laser. (Hecht, 2002)

A conceptual model that is typically used to explain these observations suggests that the slits act as two monochromatic point sources of light that oscillate in phase. The appearance of dark and bright fringes is explained in terms of the interference caused by circular waves emitted by these point sources of light. (Knight, 2008a; Young & Freedman, 2004; Hecht, 2002) Thus, the conceptual model of Young's double-slit experiment can be essentially reduced to that of a two source interference phenomenon. This phenomenon involves two sources creating circular (or sphere) waves around each other. When waves from different sources overlap, they interfere according to the principle of superposition and create a resultant wave with areas of constructive and destructive interference. (Knight, 2008a; Young & Freedman, 2004; Hecht, 2002) The phenomenon of two source interference is typically illustrated by means of representations shown in Figs 2.3a and 2.3b. These Figures are supplementary descriptions of this phenomenon: Figure 2.3a represents the phenomenon as it would appear in a real ripple tank, whereas Figure 2.3b demonstrates the waves created by both sources without any indication of their interference.

One of the general objectives of physics instruction is to help students to understand different representations of physics (Knight, 2002). Given this objective, we have investigated students' learning of the phenomenon of two source interference by evaluating their abilities to combine representations as presented in Figure 2.3. In reality, Figs 2.3a and 2.3b correspond to each other in the sense that in both Figures the distance between the sources is 1.5 times the wavelength. The grey fuzzy lines in Fig-

ure 2.3a are called nodal lines, where the waves interfere in a completely destructive manner, with the result that the amplitude of a resultant wave is zero. In Figure 2.3b, these lines pass through points where the continuous lines (representing the crests of waves) and dashed lines (representing the troughs of waves) overlap. If the sources are in phase (as in Figure 2.3), completely destructive interference occurs when the path-length difference from the sources to the point of interest reaches the values: $\lambda/2\,, 3\lambda/2\,, \ldots\,, (m+1/2)\lambda$, where λ is the wavelength and m describes the order ($m = 0, 1, 2, \ldots$).



a) b)

Figure 2.3. *Different representations of the two source interference phenomenon; in a), the interference pattern of waves are shown (modified from* http://ngsir.netfirms.com/englishhtm/Interference.htm *(valid 23.5.2014); in b), waves created by both sources are shown without any indication of their interference (modified from* (McDermott et al., 2010a)).

In Figure 2.3a, the lines where waves are the most distinguishable correspond to the anti-nodal lines. Along these lines the waves interfere in a completely constructive manner. In Figure 2.3b, these lines pass through points where a dashed line overlaps a dashed line and a continuous line overlaps a continuous line. In other words, the waves interfere in a completely constructive manner where the crests of waves from different sources overlap each other and the troughs of waves from different sources do the same. If the sources oscillate in phase, the path-length difference between the points of completely constructive interference are given the values $m\lambda$.

2.5 THE RAY MODEL OF LIGHT AND THE GEOMETRICAL IMAGE

As described in section 2.2, the ray model of light simplifies the behaviour of light waves in terms of rays, which indicates the directions of the light propagation. The ray model is based on a set of assumptions, such as

1. Light rays travel in a straight line through a single medium.
2. Two (or more) light rays can cross without affecting one another.
3. Each point of an object (self-luminous or diffusely reflecting) can emit light rays in all directions. (Knight, 2008a)

These assumptions may be used, for example, in predicting the shape of a bright area created by a light source passing through a large aperture. This type of bright area is referred to as the geometrical image (of an aperture). Examples of geometrical images are presented in Figures 2.4a and 2.4b. In Figure 2.4a, a small bulb is identified as the point source of light, which, according to assumption 3, emits light rays in all directions. According to assumption 1, these rays travel rectilinearly, and the rays that hit the mask – anywhere else than the hole – will absorb to it. Light that travels rectilinearly through the hole creates a hole-shaped geometrical image, as shown in Figure 2.4a.

In Figure 2.4b, a long and narrow light source is treated as a string of closely-spaced point sources of light. According to assumptions 1 and 3, these point sources create the hole-shaped geometrical images that overlap each other. According to assumption 2, these images do not interact (interfere) with each other, and hence together they create a geometrical image that can be observed on a screen, as can be seen in Figure 2.4b.

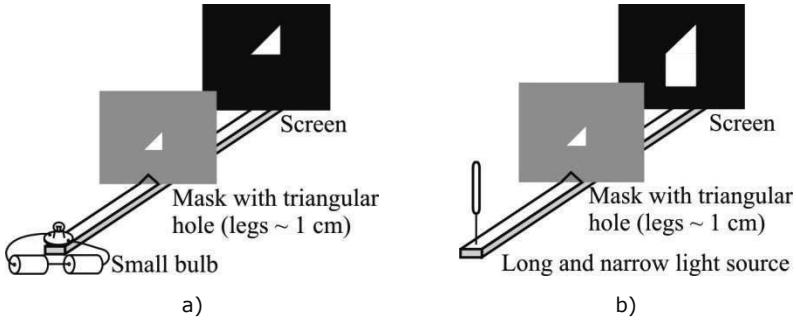


Figure 2.4. *Geometrical images created by a) a point source of light, and b) a line source of light (Modified from* (Wosilait et al. 1998; Wosilait, 1996)).

The procedures required to determine the shape of a geometrical image also create a base for acquiring an understanding of image formation in the context of lenses and mirrors. With regard to lenses and mirrors, students need to deal with the assumptions of the ray model of light and laws of reflection and/or refraction. This has been shown to be too problematic for some students to handle (Saxena, 1991; Goldberg & McDermott, 1987). The geometrical image creates a context where students may develop their understanding of the basic assumptions of the ray model of light without needing to deal with the laws of reflection and/or refraction. Thus, covering the formation of geometrical images before introducing those of real and/or virtual images may support students' understanding of image formation in optics.

2.6 THE CROSSOVER POINT BETWEEN THE RAY MODEL AND THE WAVE MODEL OF LIGHT

As explained in section 2.3, in the course of the present study the ray and wave descriptions of light were regarded as two distinct models: the ray model and the wave model of light. By following Knight's (2008a) textbook these models were treated as supplementary descriptions of light: where the validity range of the ray model ends, the validity range of a wave model will start. One should note that this distinction approximates significantly to the real relations between light waves and rays. As implied in

section 2.2, the wave description of light is valid whenever light is describable in terms of rays. In situations where the ray description is valid, the wave description of light would be unusable due to its complexity, and hence the rays are customarily used to cover the behaviour of light.

The approximate distinction between the ray model and wave model of light has its advantages with respect to students' learning of optics. It permits them to define a simple rule for the validity ranges of the ray model light and wave model of light (see (Knight, 2008a, pp. 686)). This rule is assumed to help students to recognize these validity ranges, which is further assumed to support their understanding of the ray model and the wave model of light (Knight, 2008b).

In Knight's (2008a) textbook, a point that separates the validity ranges of the ray model and the wave model of light is called a crossover point. This point can be understood by thinking of a collimated beam of light that travels straight through a circular aperture while its diameter is decreasing and considering the situation at the fixed end opposite the aperture. As a result of the diffraction of the light, the beam passing through the aperture can be considered as spreading from the middle point of the aperture, as illustrated in Figure 2.5. Figure 2.5a illustrates a situation where the spread of light at the level of a screen is less than the size of an aperture. The ray model is assumed to be applicable in this case and light can be considered as straight lines that create an aperture-sized and -shaped geometrical image on a screen. Figure 2.5b, in turn, demonstrates a situation where the spread of light at the level of the screen is greater than the size of the aperture. In this case, the ray model is invalid and the wave model of light is needed to explain the appearance of the diffraction pattern seen on the screen[10]. Thus, the crossover point between the ray model and the wave model of light can be determined by deciding whether the geometrical image of an aperture covers that of the spread of light caused by diffraction.

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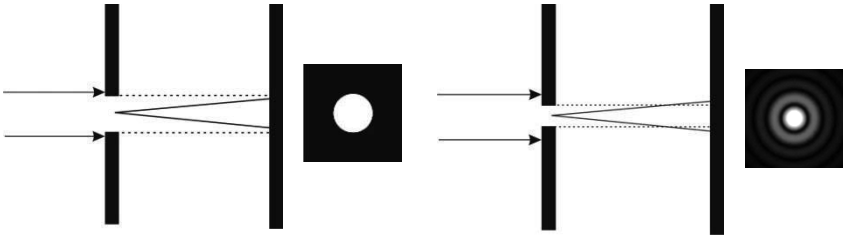
[10] Only the creation of Fraunhofer diffraction patterns is covered in the Knight's textbook (2008a).



a) The spread of light on the screen is less than the diameter of the aperture.

b) The spread of light on a screen is greater than the diameter of the aperture.

Figure 2.5. *The crossover point between the validity ranges of the ray model and the wave model of light.*

To quantize this rule, it is necessary to discover the diameter of the aperture when the width of the central maximum of the diffraction pattern is equal to the width of the geometrical image. In the Fraunhofer diffraction regime, the width of the central maximum (w) of a circular aperture diffraction pattern can be expressed in terms of the wavelength of light λ, the distance between the aperture and a screen L, and the diameter of an aperture D:

$$w \approx \frac{2.44\lambda L}{D}. \tag{2.4}$$

The coefficient 2.44 comes from the position of the first dark fringe surrounding the central maxima of the circular aperture diffraction pattern (Knight, 2008a; Hecht, 2002). Since incident light is assumed to be collimated, the diameter of the geometrical image will be the same as the diameter of the circular aperture. Hence, the crossover point between the ray model and wave model of light D_c can be derived as follows:

$$D_c = \frac{2.44\lambda L}{D_c} \Rightarrow D_c = \sqrt{2.44\lambda L} \tag{2.5}$$

In Knight's textbook (2008a), the crossover point is summarized in terms of the 1 mm rule. This rule is derived by substituting typical values for the wavelength of light and the distance between aperture and screen ($\lambda = 500$ nm, $L = 1$ m) by means of formula 2.5. According to the 1 mm rule, when light passes through an aperture greater than 1 mm in size, the ray model of

light is applicable; when light travels through an aperture less than 1 mm in size, then the wave model of light is needed to explain the size (and shape) of the bright area seen on the screen.

The derivation of the crossover point presented above can be seen as a conceptual model that is intended to clarify the validity ranges of the ray model and the wave model of light (Knight, 2008b). The approximate nature of this model, and especially the 1 mm rule, should be recognized by the instructors teaching them. We also consider it important to provide students with an opportunity to refine this model by focusing especially on the relationship between the ray description and the wave description of light, as presented in section 2.2. In the present study, however, we have taught this model in the same way as it is presented in the Knight (2008a) textbook, leaving its refinement to be undertaken in more advanced optics studies that students may possibly take at some later date.

3 Students' knowledge and reasoning

In the present study we investigate students' learning of optics. This chapter presents the ways in which we have understood what students' learning consists of and how we have approached to it in the present study.

3.1 STUDENTS' LEARNING

Intuitively, learning seems to refer to the process of extending one's knowledge: the more you know, the more you have, obviously, learnt. If this holds true, obvious questions arise concerning what knowing more means and whether it always entails learning. One answer to the latter question will be in the negative, as far as work in the field the educational psychology done by Mayer (2002) is concerned. He proposes that a student can weakly remember a few key words from the material studied without properly recognizing their meaning or how they should be used. He categorizes this type of extension of an individual's knowledge as *no learning* (see (Mayer, 2002, pp. 227)).

In addition, Mayer (2002) suggests two other ways of extending one's knowledge: *route learning* and *meaningful learning*. In route learning a student is able to memorize a fair amount of the material under study but is unable to apply it in unfamiliar situations. In the PER literature, this type of student learning is referred as *memorizing* (Wieman & Perkins, 2005; McDermott, 2001), the use of *declarative knowledge* (Arons, 1997), or *nominal knowledge* (Reif, 1995).

Meaningful learning has occurred when a student memorises most of the key facts of the material under study and is able to apply them in unfamiliar situations. In the field of PER,

meaningful learning is in line with the idea that the student will have achieved an *adequate* or *functional understanding* of the material (Meltzer & Thornton, 2012; Heron, 2004; McDermott, 2001; McDermott & Redish, 1999).

As Mayer's work suggests, students' learning refers to the extension of their knowledge and the extension of their skills to use what they know. In the present dissertation, what students know is referred to as students' knowledge, and how they use their knowledge is referred to as students' reasoning. This does not mean that students' knowledge and their reasoning can be considered as independent entities. Rather, the choice of terms – knowledge versus reasoning – indicates the perspective from which students' responses have been examined. In the case of knowledge, students' responses have been examined with the prospect of understanding *what* they know or do not know with respect of physics. In the case of reasoning, students' responses have been examined with the prospect of understanding *how* students have used their knowledge in certain situations. Both students' knowledge and their reasoning, as outlined here, provide information on different views of students' understanding of physics.

The rest of this chapter will outline the terms that have been used to describe students' knowledge and reasoning in the field of PER and also in the present study.

3.2 DESCRIPTIONS OF STUDENTS' KNOWLEDGE

In the PER literature a student's knowledge is acknowledged as being an extremely complex system (Redish, 2003). To describe it, researchers have used various terms, such as *students' difficulties* (Eunsook & Sung-Jae, 2002; McDermott, 2001); *conceptions* with various prefixes, such as *mis-* and *pre-*, (Leinonen, Asikainen, & Hirvonen, 2013; Miller, Lasry, Chu, & Mazur, 2013); and various types of *models – mental, hybrid,* and *conceptual* (Tongchai, Sharma, Johnston, Arayathanitkul, & Soankwan, 2011; Bao & Redish, 2006; Ambrose, Shaffer, Steinberg, &

McDermott, 1999). The use of these and other terms has obviously aimed at capturing students' knowledge partially, focusing on the features that are considered relevant. The emphases of these features have largely depended on the particular research aim (Heron, 2004). For example, a study that aims at developing an effective curriculum hardly needs as complex a description of students' knowledge as a study targeting the development of a theoretical framework for the context dependency of students' reasoning of physics.

The use of these simplified terms has suggested that researchers have made certain assumptions regarding the nature of students' knowledge. Perhaps the most well-known, and yet somewhat contrasting, sets of assumptions have discussed whether students' knowledge emerges from precompiled and theory-like systems[11] or from fragmented and units created *in situ*[12]. In the field of Science Education, some studies have debated which of these two sets of assumptions is the more valid (diSessa, Gillespie, & Esterly, 2004). In the field of PER, in turn, researchers have generally treated them as complementary sets of assumptions, as Redish's (2003, p. 21) argument implies: "*the decision as to which [set of the assumptions] is more appropriate is <u>an empirical one</u>*". This indicates that both sets of assumptions can be considered to be valid, and neither of them should be abandoned simply to unify background assumptions regarding students' knowledge. Bao and Redish (2006) have suggested that theory-like systems and fragmented knowledge units could be seen as the opposite extremes of students' knowledge. A real student's knowledge is likely to exist somewhere between these two extremes, based on both theory-like and fragmented elements. The present study has been consistent in its use of this assumption: we have not adopted a strictly predetermined stance on what students' knowledge consists of. Instead, we have refined our assumptions of students' knowledge while obtaining a better understanding of the students' responses received and also of the related literature. As a consequence, in the

[11] For example, McCloskey's (1983) naive theories of motion.

[12] For example, diSessa's (1993) phenomenological primitives.

present study students' knowledge has been described in terms of conceptions and difficulties. The following subsections 3.1.1 and 3.1.2 will discuss the meaning of these terms.

3.2.1 Conceptions

The majority of PER researchers seem to agree that the term *conception* refers to the pre-existing ideas that students bring into the physics classroom as an inheritance of their earlier instruction and/or of experiences obtained in the physical world. Researchers, however, appear to disagree over what these ideas consist of. It has been argued that such conceptions may be strongly held and stable cognitive structures (Redish E. F., 2003; Hammer, 1996a; Hammer, 1996b), but they are also treated as loosely held and unstable knowledge units (Miller, Lasry, Chu, & Mazur, 2013; Leinonen, Asikainen, & Hirvonen, 2013; Redish, 2012). In addition, some researchers have used the term *conception* merely to describe a recognizable pattern in students' responses, while making no assumptions whatsoever about the stability of students' knowledge (Hammer, 1996b). This practical stance largely corresponds to our use of the term *conception*. In other words, we have mainly used it as a straightforward description of the regularities observed in students' responses. These regularities have, however, been assumed to indicate students' permanent ideas, since they are typically observed before and after instruction or after a long period of time has lapsed since the actual instruction. However, we would not claim that students' conceptions must be strongly held in a variety of different contexts, for example. Hence, we conclude that our use of the term *conception* has largely been descriptive, with the aim of presenting the regularities observed in students' responses. If these regularities have been inconsistent with respect to physics, the prefix *mis*(conception) has been used to highlight this perception.

In the present study, students' conceptions are assumed to reflect their *factual* and *conceptual knowledge*. The factual knowledge refers to facts that a student knows to be true, whereas the conceptual knowledge refers to the interrelation-

ship between these facts (Krathwohl, 2002). With the aid of the conceptual knowledge students may combine known facts to larger networks that have greater explanatory power than separate facts alone (Reif, 1995). This explanatory power manifests itself as a student's ability to use known facts flexibly in *qualitative reasoning*, for example. This type of reasoning corresponds to how experienced physicists use their knowledge in problem solving (Van Heuvelen, 1991), and hence it is considered an important goal of physics instruction (Mestre, 2001).

By investigating students' conceptions, we have examined their factual and conceptual knowledge with the intention of understanding which facts and interrelationships between the facts exist and then also what is missing. Thus, with this information we have aimed at understanding students' learning of physics and also at improving their instruction.

3.2.2 Difficulties

In addition to the term *students' conception*, the term *students' difficulty* has often been used in the PER literature. In contrast to students' conceptions, the term students' difficulty is more noncommittal regarding the assumptions involved in establishing the nature of students' knowledge (Hammer, 2000). In other words, students' difficulties can be either precompiled or created *in situ*, while they may be both stable and unstable, but in any case students' difficulties interfere with their learning of physics. Students' difficulties typically refer to the type of students' errors that reflect the presence of knowledge rather than its absence (Heron, 2004). This description corresponds closely to the meaning of students' misconceptions. However, its meaning is somewhat broader than that of misconceptions (McDermott, 2001). Students' difficulties do not always arise from their misconceptions, which may consist of inappropriate factual and/or conceptual knowledge; the difficulties may also arise from students' inaccurate *procedural knowledge*. This type of knowledge refers to students' skills used in performing certain procedures (Krathwohl, 2002; Reif, 1995), such as adding vectors appropriately. This does not mean that students' procedural

knowledge would necessarily be independent of their factual and conceptual knowledge. On the contrary, these students' knowledge types seem to be interwoven, as the findings in a study by Flores, Kanim, & Kautz (2004) suggest. For example, they have found that students tend to use the Pythagorean Theorem to determine the magnitude of the resultant of two non-perpendicular vectors. They have suggested that students have used this incorrect procedure because they have believed that the Pythagorean Theorem provides a universal rule for finding the magnitude of the resultant of any two vectors (Flores, Kanim, & Kautz, 2004). This belief seems to correspond to what we perceive as (mis)conception, emerging from students' conceptual knowledge.

To sum up, the origin of students' difficulties – whether they arise from factual, conceptual, or procedural knowledge – is difficult to determine unambiguously. Thus, such a distinction has been omitted from the present study. Instead, we have used the term *students' difficulty* to describe a type of inconsistences that students have experienced in their content knowledge of physics. Thus, the term *students' difficulty* has referred to the absence of factual knowledge; it has served as a synonym for *students' misconceptions*; and it has described occurrences of resultant students' inability to perform procedures needed in physics.

3.3 STUDENTS' REASONING

In the PER literature students' reasoning has often referred to the process that makes their understanding of physics evident to others. This has been the case especially when reasoning is investigated by using novel situations that have not been explicitly covered in earlier instruction (McDermott, 2001). The novelty of these situations aims at ensuring that students are unable to respond to them successfully by merely relying on ready-made answers learnt by heart in advance. Instead, students need to apply what they know, making, at the same time, their understanding at least partially visible to others.

Considering students' reasoning as a process that makes an individual's understanding visible to others raises questions, such as where that process starts, where it ends, and what happens between start and end. It has been hard to find answers to questions of this nature in the PER literature. Instead, Walton (1990) (from the field of philosophy) has suggested that reasoning is a process where a person shifts from their premises towards their conclusions by following certain procedures. Walton's suggestion matches the idea that optics is taught in terms of conceptual models, as argued in section 2.3, above. The selection of an appropriate conceptual model and recognizing its assumptions (e.g., idealized entities) can be seen as the premises of reasoning that students need to recognize in order to apply this model successfully. For example, when a student predicts the shape of a geometrical image, s/he may take the ray model of light and its assumptions as the premises of their reasoning. In addition to such premises, a student needs to master certain procedures, such as creating a ray diagram that is consistent with the rectilinear propagation of light. As result of correctly recognized premises and carefully implemented procedures, the student should end up with a correct conclusion, as a final step in his/her reasoning.

Thinking about students' reasoning in terms of premises, procedures and conclusions has helped us to conceptualize the context-dependency of students' reasoning, as sub-section 3.4.2 presents. Prior to this subsection, however, we will discuss the ways in which the context-dependency of students' reasoning has been approached in the PER literature.

3.4 CONTEXT-DEPENDENCY OF STUDENTS' REASONING

The context-dependency of students' reasoning appears whenever students provide a correct response to a task but an incorrect response to a closely-related task. These tasks have typically required students to apply the same physics subject matter but

have used different wording and/or pictorial representations[13] (Stewart, Griffin, & Stewart, 2007; Meltzer, 2005; Palmer, 1997). Students' inability to respond to closely-related tasks has suggested that they pay more attention to the more superficial features of tasks – wording and pictorial representations – than to the intended physics subject matter. This has supported the assumption that students' knowledge of physics is fragmented (Stewart et al., 2007). Stewart, Griffin, and Stewart (2007) have argued that in some contexts the gaps between students' knowledge units create uncertainty in their reasoning. As a result of students' uncertainty, they tend to rely more on their intuition than their content knowledge of physics, with the result that their reasoning comes to depend on the context (Stewart et al., 2007). In addition to students' uncertainty, the context-dependency of students' reasoning has been explained in terms of students' *resources*, as described in subsection 3.4.1.

3.4.1 Resources

To enhance the extent to which students' learning has been conceptualized in the field of PER, Hammer and his colleagues have proposed the notion of a *resource-based framework* (Hammer et al., 2005; Hammer, 2000). Much of this framework is consistent with the work of Smith, diSessa and Roschelle (1993), who have criticized the *misconception research* that has commonly been conducted in the fields of PER and Science Education. This line of research has often set certain assumptions as the basis for students' learning, such as students' knowledge consists of misconceptions that need to be replaced with conceptions that are consistent with scientific concepts. According to Smith et al. (1993), this assumption oversimplifies the complexity of learning, and yet it is inconsistent with the assumption that new knowledge is built on prior knowledge[14]: how can something be built on that first needs to be replaced? According to Smith et al. (1993), this is logically impossible.

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[13] Here, the pictorial representation refers to pictures and sketches used to clarify what is asked in a task assignment.

[14] The basic assumptions of constructivism (Bransford et al., 2004).

Despite their criticism, Smith et al. (1993) acknowledge the empirical value of misconception research, but they argue that it is a time to move on and develop a more comprehensive description of students' learning. The resource-based framework can be seen as a response to Smith et al.'s (1993) wish. The framework describes a student's knowledge as a *state* that can be refined rather than replaced in the process of learning (Hammer et al., 2005). A student's state of knowledge is described in terms of resources which represent what they know involving all types of knowledge – factual, conceptual, procedural, and others[15]. A resource can represent undividable knowledge units, such as diSessa's (1993) phenomenological primitives, or more stable theory-like knowledge systems, such as McCloskey's (1983) naïve theories of motion. A student's knowledge is assumed to consist of a wide range of different resources. Some of these resources are activated when a student reasons in a certain situation. In other words, the activation of a student's resources is assumed to depend on a context that at the same time explains why his/her reasoning may depend on a context.

The activation is assumed to happen rather systematically as a result of *framing* (Hammer et al., 2005). This refers to students' expectations of how they should behave and what knowledge they should express in the situations in which they find themselves. As the outcome of framing, a student activates a set of local and/or global resources which will influence his/her behaviour in a given situation. The framing can happen consciously or unconsciously, but, in either case, students' expectations interpreted from a given context determine what knowledge becomes available to them and how they reason in a given situation.

The resource-based framework has extended the ways in which students' reasoning has been examined. For example, it has permitted the discovery of productive resources (Harrier et al., 2013). These resources consist of students' ideas that are in-

[15] For more information, see (Harrier, Flood, & Wittman, 2013).

correctly extended in some contexts but can serve as a good base for learning physics in other contexts.

In sub-study 3 we found the resource-based framework to be slightly impractical since our data was indescribable in terms of the acknowledged conceptual resources, such as diSessa's (1993) phenomenological primitives. Rather than attempting to launch a new type of conceptual resource, we adopted the Johnson-Laird mental model theory (Johnson-Laird, 1983), which will be described in subsection 3.4.2, below.

3.4.2 Propositional representations, mental models, and images

The Johnson-Laird mental model theory argues that a human mind consists of at least three types of mental representations: *propositional representations*, *mental models*, and *images*. They all refer to different levels of human understanding and its development, and also play a role in the process of reasoning.

Propositional representation stands for the most superficial level of human understanding. In concrete terms, it refers to a person's ability to repeat a piece of information (word, sentence, equation, etc.) without been able to connect it to his/her prior knowledge. As a consequence, a person is unable to understand the meaning of the information. The mental model is a type of representation that permits a person to connect a new piece of information to his/her prior knowledge. As a consequence, a person is able to obtain a deeper understanding of that information and to use it flexibly in novel situations. Images are specifications of the mental models that a person creates while running the model in a certain situation. Thus, the images include features that correspond closely to real-world objects and events.

By means of these mental representations an understanding of a new piece of information can be explained in terms of its syntactic and semantic structure. In a language, for example, the syntactic structure refers to a grammar, status of words, and their order. The semantic structure, in turn, describes the entities, objects, or events in which the given information – words

and phrases – refers to in a real-world context. According to the theory, when a new piece of information is told to a person, its syntactic structure is first presented as propositional representations in the person's mind. These propositional representations can develop as mental models as soon as the semantic structure of given information becomes evident to a person. Thus, the theory suggests that the creation of mental models, and hence human understanding, is based on grasping the semantics of the new piece of information. The semantics of given information can be inferred not only from the information itself, but also from a context where it is given. Therefore, the Johnson-Laird mental model theory (Johnson-Laird, 1983) can be used in describing the context dependency of students' reasoning of physics.

In addition, the theory is consistent with the idea that reasoning is considered in terms of shifts from premises toward conclusions (see section 3.3). According to the theory, when a person is reasoning, s/he aims to create mental models of the premises of his/her reasoning (Johnson-Laird, 1983). In the process of reasoning, a person aims to reach the most suitable conclusion(s) of reasoning by manipulating these models by means of procedures of mind. If the creation of mental models on the premises of reasoning depends on a context, then the process of reasoning itself also depends on a context.

With respect to the theory, the context-dependency of students' reasoning of physics can be seen as a consequence of forming mental models from the semantics that can be inferred from a context. In other words, the context dependency of students' reasoning arises from students' limited ability to grasp the semantic structure of given information (i.e., what the words, concepts, and drawings presented in a question actually refer to). Students may grasp the semantics of the given information as desired in one context, but fail to do so in other contexts, thus causing the context-dependency of students' reasoning.

If students are unable to find the semantic meanings of the premises of reasoning, then their reasoning is based, at least partially, on propositional representations (Greca & Moreira, 1997).

If this is the case, then students' reasoning relies on the syntactic structure of the premises of reasoning, that is, superficially memorized pieces of information (words, concepts, equations). In that case, students will probably be unable to demonstrate a robust understanding of physics content in their reasoning.

In sub-study 3, the Johnson-Laird mental model theory helped us to make sense of students' responses that otherwise appeared anomalous. Thus, this particular theory has been useful and, as speculated in article IV, may be adaptable to the resource-based framework of students' reasoning. In that instance, the propositional representations and mental models could be seen as certain types of conceptual resources together with diSessa's (1993) phenomenological primitives.

4 Study context and approach

The present study has been conducted at the Department of Physics and Mathematics at the University of Eastern Finland (UEF). In the course of the study, the physics education given in the department has mainly consisted of lecture courses and separate courses for laboratory work. The lecture courses are rather conventional, consisting of weekly lectures and recitation sessions. In lectures, a lecturer typically presents a topic of physics with the aid of PowerPoint slides and handwritten examples, while the students simply listen and take notes. Outside the lectures, the students are supposed to deepen their knowledge by solving weekly homework assignments related to the lecture course. The solutions to these assignments are presented at weekly recitation sessions. In these sessions, students typically check their solutions or copy them from the board. This type of physics education corresponds to what we call *conventional lecture-based physics instruction*, or in short lecture-based instruction.

Students participating in sub-studies 1-3 have to a greater or lesser extent been exposed to this type of physics teaching throughout their university studies. In sub-study 1, students were taking a third-year quantum physics course; they had completed relevant courses on electromagnetism and optics more than 6 months prior to the gathering of the data. This was assumed to indicate the extent of what they had learnt permanently from conventional lecture-based courses dealing with electromagnetism and optics.

Sub-studies 2 and 3 were conducted in the context of a first-year physics course, Basic Physics IV (BP-IV). The course instruction itself slightly differed from that of a conventional lecture course, and hence it is presented in greater detail in section

4.1. Sections 4.2 and 4.3 present the approach taken in the present study and also the underlying principles of the analysis made of students' responses.

4.1 BASIC PHYSICS IV

BP-IV is an introductory physics course that covers the basics of waves, optics, and modern physics by following the textbook Physics for Scientists and Engineers (Knight, 2008a). Students participating in BP-IV were typically freshmen or sophomores majoring in physics, mathematics, chemistry, or computer science aiming at graduating as teachers or scientists. Approximately, 80% of the students had previously studied optics as part of their physics studies while at upper secondary school.

BP-IV was lectured by a teacher who has actively contributed to the fields of PER and Science Education. Thus, the lectures aimed at supporting students' active engagement with the aid of stop-to-think questions included in the textbook of Knight (2008a). These questions were used once or twice in the course of each 90-minute lecture period. In addition, the web-based applets and demonstrations often refreshed the presentation of the physics subject matter covered during lectures.

Weekly homework assignments were based on Knight's (2008a) textbook, consisting of both quantitative end-of-chapter exercises and also qualitative conceptual tasks adopted from the PER literature. The correct solutions to the assignments were presented in weekly recitation sessions along with the presentation of related demonstrations and web-based applets. Occasionally, the students were offered additional exercises to be solved at the end of the recitation sessions.

As a part of sub-study 2, two tutorials selected from the Tutorial in Introductory Physics curriculum (McDermott et al., 2010a) were also used. Each tutorial was conducted in a 90-minute lecture period, thus occupying four lecture periods out of a total of 40.

Despite the special features of BP-IV, it has been treated as a conventional physics course. This generalization has been made because BP-IV has mainly consisted of conventional components in the course of this study: lectures, homework assignments, and recitations sessions. In addition, the lectures have mainly focused on the presentation of the content, while the recitation sessions have been used for presenting the solutions to the homework assignments. The use of stop-to-think questions, demonstrations, web-applets, and tutorials has been considered to be only minor modifications in the structure of a conventional physics course.

4.2 MIXED METHODS APPROACH

Our research approaches that were made in the study contexts discussed above closely correspond to those used in *mixed methods research* (Cresswell, 2009; Teddlie & Tashakkori, 2009). This correspondence is evident from the observation that we have combined the qualitative and quantitative data sources in each sub-study. These data sources have been combined so that we could obtain as comprehensive evidence as possible related to the students' learning of optics. In addition, we have mixed these data sources, since this type of mixing is much appreciated in PER (Beichner, 2009).

Our mixing of qualitative and quantitative data sources corresponds to the *embedded mixed methods design* (Cresswell, 2009). This means that in each sub-study the mixing has occurred within a broader research design(/strategy). These designs have consisted of a survey in sub-study 1, an experiment in sub-study 2, and a case study in sub-study 3. These research designs provide an outline of how we have approached students' learning of optics in each sub-study. In addition, these designs have influenced the selection of the data gathering *methods* used in the sub-studies. These designs and methods are further discussed in chapters 5, 6, and 7 as aspects of the overviews of sub-studies 1-3.

4.3 CONTENT ANALYSIS AND THE PRESENTATION OF THE RESULTS

Our analysis of students' responses in all sub-studies closely corresponds to *content analysis research* (Fraenkel & Wallen, 2000). This type of research aims at providing replicable inferences from texts in their contexts of use (Krippendroff, 2004). Here, the text refers to all sorts of symbols that may deliver the meaning, such as equations, diagrams, and calculations. In the content analysis, this type text can be categorized into content-related categories (Elo & Kyngäs, 2008). These categories do not simply squeeze the content of a text into a more compact form but may also reveal its hidden structure. Recognizing this structure permits researchers to obtain a broader meaning of the text.

In the present study, the analysis of students' responses has corresponded to content analysis research in the sense that initially the students' responses were transcribed as text. This text has contained students' written explanations, their drawings, and their selections in response to multiple-choice questions. The content of this text has then been evaluated in terms of relevant conceptual models of physics, concluding with a rough categorization, such as correct, nearly correct, and incorrect students' responses. These approximate categories have further been analyzed in order, for example, to identify the types of errors students had made in their responses. The errors identified have created subcategories, whose content has been compared to the findings of previous studies in order to reveal what was new in our own results. Finally, the contents of the categories and sub-categories have been projected onto the wider perspectives of students' learning of optics as they arise in the goals of a particular sub-study.

The unit of our content analysis has been the student's *idea* that reflects his/her knowledge about relevant conceptual models of physics. In sub-studies 1-3 this unit has been labelled in terms of conceptions, difficulties, and paralleled to students' mental models or their propositional representations. This unit may have contained a form of a word(s), sentence(s), draw-

ing(s), or selection(s), or any combination of these. However, the unit was also obliged to permit us to infer hypothetically what a student has previously known, or not known, or how they have used their knowledge in a given situation.

As a result of this type of content analysis, we have categorized students' responses unambiguously. Each student's response has been placed in a single respond category. If a student's response has contained features from two or more categories, this has constituted its own category, or it has been categorized based on its main features. In all of the sub-studies, the final categorization of students' responses has taken several analyzing rounds. During these rounds the criteria for the categories have been refined in order to capture the most relevant features of students' responses with respect to the scope of the research. These criteria have been devised with the aim of presenting the result sections of articles I-IV as transparently as possible.

The quantity of categories has been described in terms of descriptive statistics: frequencies, proportions, means, and standard deviations.

In sub-study 2 the *chi-square test for homogeneity* (Sheskin, 2003) was used to infer the similarity of two independent data sets (see the article III). The test permitted us to justify combining the various data sets obtained in consecutive years. The test itself was conducted by determining the expected frequencies (E_{ij}) from the students' correct and incorrect responses (O_{ij}) obtained annually, using the following equation

$$E_{ij} = \frac{(O_{i.})(O_{.j})}{N}, \tag{4.1}$$

where N is the total number of students' responses. Then the value of the χ^2test variable was calculated by comparing the expected and obtained frequencies with the aid of the following equation:

$$\chi^2 = \sum_{i=1}^{r}\sum_{j=1}^{c}\left[\frac{\left(O_{ij} - E_{ij}\right)^2}{E_{ij}}\right]. \tag{4.2}$$

With the aid of the chi-square distribution table, the value of χ^2 was converted to a p-value. If the p value was greater than 0.05, then the students' response distributions obtained in consecutive years did not differ significantly. Hence it was considered appropriate to merge the data sets collected in consecutive years into one.

In addition to the chi-square test for homogeneity, the *McNemar test* (Sheskin, 2003) was used in sub-study 2 to indicate the impact of the tutorial tasks on students' learning. More precisely, the test was used to discover whether the improvements in students' responses were statistically significant or not. For the test, the students' knowledge was evaluated before (pre-responses) and after (post-responses) they had performed the tutorial tasks. These responses were categorized as correct or incorrect responses. The frequencies of these categories were cross-tabulated, as shown in Table 4.1. This Table took into account only those students' who had provided both pre- and post-responses.

Table 4.1. *Frequencies organized to conduct the McNemar test*

	corrects post-responses	incorrect post-responses
incorrect pre-responses	a	b
correct pre-responses	c	d

The value of the χ^2 test variable was determined with the aid of the following equation:

$$\chi^2 = \frac{(d-a)^2}{(d+a)}. \tag{4.3}$$

The value of the test variable was converted to p-values with the aid of a chi-square distribution table. If the p-value was less than 0.05, the improvement was considered to be statistically significant.

5 Overview of sub-study 1

Sub-study 1 focused on students' learning of the electromagnetic nature of light. More precisely, we investigated students' conceptions of the electric and magnetic fields and their interrelations after they had completed university courses in electromagnetism and optics. Previous studies had identified various difficulties encountered by students in using the concept of field in their reasoning (Furiò & Guisasola, 1998; Törnkvist, Pettersson, & Tranströmer, 1993). In addition, students were often shown to be unable to recognize the symmetric interrelations of the electric and magnetic fields (Guisasola, Almudi, & Zubimendi, 2004; Ambrose et al., 1999; Bango & Eylon, 1997). These findings suggested that a field-based description of light may be difficult for students to grasp, since it requires an understanding of the basic assumptions of the field concept – e.g., the field exists in every point of space – and the interrelationships of the electric and magnetic fields.

In sub-study 1 the students' conceptions of the electric and magnetic fields and their interrelations were investigated in different contexts. The contexts chosen were a charge, a charging capacitor, an electromagnetic induction, and an electromagnetic plane wave. These contexts were chosen since the meaning of a field concept grows from the model of the interaction of the charges into a description of light. Thus, using these contexts, we were able to obtain an extensive description of students' conceptions of the electric and magnetic fields and their interrelations. This description, in turn, was supposed to provide information on students' prerequisites for understanding the electromagnetic nature of light. In addition, these contexts seemed to create a useful base for the development of instruction that would aim at improving students' understanding of the field concept and of the electromagnetic nature of light.

5.1 SURVEY DESIGN AND DATA-GATHERING

In sub-study 1 data was gathered with the aid of a *cross-sectional survey* (Cresswell, 2009). It served as a straightforward method of indicating what students had learnt during their earlier university studies that had focused on electromagnetism and optics. The survey was implemented in a paper-and-pencil format consisting of four tasks, each covering a single context that was designed to be addressed in sub-study 1. The tasks were based on earlier studies (Ambrose et al., 1999; Eylon & Ganiel, 1990) and upper-secondary and introductory level textbooks. (Hatakka, Saari, Sirviö, Viiri, & Yrjänäinen, 2006; Knight, 2008a). The tasks are presented in article I.

The survey was conducted at the start of the Autumn semester in 2008. The relevant background courses in electromagnetism and optics had ended more than 6 months before the data was gathered. The data-gathering was implemented during a 45-minute lecture period. It permitted us to ensure that the students responded without resorting to external information sources such as textbooks or the internet. A total of 33 students responded to the survey. They were not informed in advance about the testing so as to ensure that their responses would reflect what they had learnt from their previous studies of electromagnetism and optics. All of the participants had completed the course in electromagnetism at university but not the course in optics. However, dividing the students into sub-groups according to their background studies would have provided no essential additional information. Thus, a total of 33 students were treated as a single group.

Recognizable patterns of students' responses were categorized into content-specific categories reflecting students' factual and conceptual knowledge concerning the electric and magnetic fields and their interrelationships. The frequencies of these categories were calculated, and the categories and frequencies were presented in Tables. Finally, the results obtained were collated by holding a discussion of the possible origins of the students'

incorrect conceptions and of how they could be tackled with the aid of instruction in electromagnetism and optics.

5.2 MAIN RESULTS AND DISCUSSION

The results of sub-study 1 demonstrated that students held various incorrect conceptions about the interrelationships of electric and magnetic fields. In the context of a charge, 15% of the students suggested that a magnetic field only exists around a charge that moves uniformly (constant speed to a certain direction). In the contexts of a charging capacitor and of electromagnetic induction, approximately 30% of the students were unable to recognize the presence of an induced magnetic field or electric field. And finally, in the context of an electromagnetic plane wave, 70% of the students demonstrated that they held a conception according to which the electric and magnetic fields are independent of each other.

The students' incorrect conceptions reflected their lack of factual and conceptual knowledge about fields and their interaction. More precisely, many students were unable to recognize that a changing electric field creates a magnetic field, and *vice versa*. Due to their lack of these crucial pieces of knowledge, students demonstrated that they had difficulty in understanding the interrelationships of electric and magnetic fields. Especially in the context of the electromagnetic plane wave, a large proportion of the students (70%) incorrectly treated these fields as independent entities. This indicated that the field-based description of light is difficult for students to grasp. This, in turn, suggested that to improve students' learning about the electromagnetic nature of light, more attention should be paid to teaching the interrelationships of the electric and magnetic fields. This was in fact the original scope of the present study, which was changed due to reasons explained in section 1.3.

6 Overview of sub-study 2

Sub-study 2 focused on the adoption of the Tutorials in Introductory Physics curriculum (McDermott et al., 2010a). This curriculum, later referred as tutorials, has proven effective in overcoming students' difficulties in learning physics (McDermott, 2001). Nevertheless, its use requires additional resources that go beyond from those obtainable for an individual instructor, such as arranging small classroom sessions with two trained instructors.

To make the tutorials more accessible for instructors at different institutes, sub-study 2 has provided a fairly easy way to adopt the tutorials in a lecture hall setting. The following chapter argues that our way of using tutorials differs essentially from other ways presented in the PER literature. It also emphasises the benefits of our way of using the tutorials as an initial stage in their adoption. The chapter presents evidence that suggests that way we have used the tutorials has supported students' learning of the basics of the ray model and the wave model of light in the course of years 2011-2014. The presentation of these results covers more data than is reported in articles II and III. The unpublished results show that the trend of the results as presented in the articles has remained in the course of this study. Finally this chapter discusses the benefits of different ways of implementing the tutorials. In addition, it highlights some of the hypothetical factors that may explain why some implementations support students' learning more than others.

6.1 MOTIVATION FOR THE DEVELOPMENT OF AN ALTERNATIVE METHOD OF ADOPTING TUTORIALS

The Tutorial in Introductory Physics curriculum consists of context-specific tutorials which each involve a pretest assignment, a

worksheet, homework, and a posttest assignment. These instructional materials are published in three books: an instructor guide[16] (McDermott et al., 2003), workbook (McDermott et al., 2010a), and homework assignments (McDermott et al., 2010b). The instructor guide contains pretest and posttest assignments and instructions about how to use the tutorials. The workbook contains worksheets that are meant to be covered in tutorial sessions, where students can consult with an instructor(s), whereas the homework assignments provide material that students are expected to go through by themselves.

The following subsections 6.1.1 and 6.1.2 describe the implementation of tutorials in small classroom and lecture hall settings, respectively. In subsection 6.1.3, we argue why an alternative way of implementing of tutorials is needed to permit wider use of tutorials per se.

6.1.1 Tutorials conducted in a small classroom setting

The tutorials are most commonly used in small classroom settings (McDermott et al., 2003). In a conventional physics course the use of tutorials has taken place in weekly recitation sessions substituting the presentation of a weekly homework assignment (McDermott, 2001).

The content of the tutorials is based on conceptual models of physics that are typically covered at an introductory level. The tutorials aim to address those aspects of these models that are found difficult for students to grasp after attending lectures. These difficulties are tackled by engaging students in applying their knowledge in a pretest, a tutorial session, homework, and a posttest.

The pretest precedes a tutorial session, and it contains a few paper-and-pencil tasks that ask students to apply their content knowledge of physics that will have been recently lectured on in unfamiliar situations. In the past, the pretest was conducted in paper-and-pencil format either before or at the beginning of weekly tutorial sessions (McDermott et al., 2003). Nowadays,

[16] The guidebook is not typically available in bookstores; it needs to be ordered from the publisher separately.

students take a pretest online before the tutorial session (see, e.g., (Lindsey, Heron, & Shaffer, 2009)). The pretest serves two purposes: (1) it informs instructor(s) about the level of students' understanding of physics content after it has been lectured on; (2) it informs students about what they are expected to be able to deal with by the end of a course in terms of the physics content (McDermott, 2001).

After the pretest, the students participate in the weekly tutorial session (50 min/week). In each session, the approximately 20 students are divided into groups of three or four. These groups work through a tutorial worksheet which typically involves 3-5 pages from the tutorial workbook (McDermott et al., 2010a), under the guidance of two instructors. The worksheet divides the conceptual model being taught into statements, questions, and hands-on tasks. These activities aim at providing necessary items of information from which students should be able to construct the taught conceptual model by themselves. Students are expected to collaborate with their peers while working through the worksheet. In addition, students may negotiate with their instructors whenever necessary. The instructors are typically graduate students who have been trained to work as tutorial instructors[17]. The role of the instructors is to support students' thinking by teaching them questioning rather than by telling. Thus, these instructors guide not by providing answers to worksheet tasks but rather by encouraging students to examine their thoughts to see whether they are consistent with other evidence obtained during the tutorial session. (McDermott, 2001)

After the tutorial session, the students are expected to tackle the tutorial homework assignment (McDermott et al., 2010b). The homework assignments consist of similar, but not identical, tasks to those in the tutorial worksheets. The students return their homework assignments, which will be graded and subsequently returned to them by the instructors. This allows the stu-

[17] During their training the instructors respond to the pretest, go through the tutorials worksheet, and discuss the most common students' difficulties and strategies and how to address them during a tutorial session (McDermott et al., 2003).

dents to receive feedback on whether they had learnt the physics content as expected. (McDermott et al., 2003)

The posttest is typically used as part of a course or midterm exam. It corresponds to the pretest, although it is not identical to the pretest (McDermott, 2001). By comparing students' answers to a pretest and a posttest given in a particular tutorial, useful indicators of the effectiveness of a tutorial on students' learning can be found.

Much of the content of the tutorials has been developed iteratively; tasks in the worksheets and/or homework assignments are refined repeatedly in order to help students to maximize their learning gains. Students' learning gains are typically compared to those of the tutorial instructors, since they will have responded to the similar questions in their preparation session (McDermott, 2001). If students achieve scores that are as high as those of their instructors, then a particular tutorial is regarded as effective by the tutorials developers (Kryjevskaia, Stezer, & Heron, 2011).

The developers have found that the tutorials are most effective when they are conducted in a small classroom setting (McDermott et al., 2003). The following subsection describes how the tutorials might also be used in a lecture hall setting.

6.1.2 Use of the tutorials in a lecture hall setting

The motive for implementing the tutorials in a lecture hall setting arises from a number of challenges encountered in implementing them in the small classroom setting (McDermott et al., 2003). The *interactive tutorial lecture* is the developers' format for using the tutorials in a lecture hall setting. In this format, a lecture period (50 min) is divided into two modes: group work and class discussion. During the group work, students work through a certain part of the tutorial worksheet with their neighbours for 5-10 minutes, while the lecturer and other instructors move around the room, teaching individual students by questioning. Following the group work mode, the lecturer will then engage the whole class in a discussion, at the same time aiming at guiding them towards articulating important ideas covered previ-

ously in the tutorial worksheet. In addition to these two modes, test questions are used to evaluate the students' learning at various stages in the lecture period (Personal communication with members of the Physics Education Group at the University of Washington, 2010).

6.1.3 The need for an alternative adaptation of the tutorials

Despite two alternative methods of implementing the tutorials, both of them may be too demanding for an instructor to implement. The small classroom implementation requires organizing small classroom sessions with two well-prepared instructors. These changes typically require an institutional level of commitment to the use of the tutorials (Finkelstein & Pollock, 2005). This level of commitment can be difficult to obtain without having factual evidence about the benefits of the tutorials in a particular institution (Turpen & Finkelstein, 2008).

In fact, the format of interactive tutorial lectures requires fewer external resources and is an easier way to implement the tutorials. However, it requires engaging students in the whole-class discussion, which has proven to be a demanding task even for experienced instructors (Fagen, Crouch, & Mazur, 2002; Turpen & Finkelstein, 2009). In consequence, the interactive tutorial lectures may be much too demanding a format for an instructor who may have become accustomed to traditional lecturing but is implementing the tutorials for the first time.

The whole-class discussion is also problematic with regard to indicating the effectiveness of the tutorials. The problem is that a whole-class discussion – a dialogue between a lecturer and students – may support the students' learning by itself (Beatty, Gerace, Leonard, & Dufresne, 2006). In that case, it will be difficult, if not even impossible, to distinguish between learning that has occurred as a result of tutorial tasks and learning resulting from a lecturer's dialogue with students. As a consequence, interactive tutorial lectures may prove to be instructor-dependent and thus a biased indication of the effectiveness of the tutorials.

In sub-study 2, we did not use whole-class discussions but implemented the tutorials in a lecture hall setting. This has been established as a form of *tutorial intervention* that was designed to test the impact of tutorial tasks on students' learning of physics. Our intervention consisted of two modes of instruction during which (1) students responded to test questions, and (2) students worked on tutorial tasks. Combining these modes, the impact of the tutorial tasks was tested in the case of tutorials dealing with *Two Source Interference* and *Light and Shadow*[18]. These tutorials were suitable since they initiated a set of tutorials aimed at improving students' learning of the ray model and the wave model of light.

Sections 6.2 and 6.3 which follow describe how these tutorials were prepared for the tutorial intervention and how their impact on students' learning was investigated.

6.2 PREPARATIONS AND PRACTICES OF THE TUTORIAL INTERVENTION

Prior to the implementation of the intervention, the tutorial worksheets were translated into Finnish. In addition, we prepared answer sheets related to the test questions to be used in evaluating students' learning during the intervention. The material distributed to the students at the beginning of the intervention consisted of the translated tutorial worksheet and the test question answer sheets.

The answer sheets provided only a space for the students' responses without showing the actual test questions. These questions were displayed on a large lecture hall screen via a computer and a data projector. By displaying the test questions solely on the screen, we could control the students' response time. This helped us to ensure that the students all worked at

[18] The tutorials Two Source Interference and Light and Shadow can be found in (McDermott et al., 2010a) pp. 213-217 and pp. 185-188, respectively.

approximately the same pace, and the majority of students had sufficient time to respond to each test question.

Both implementations of the intervention were conducted in a lecture hall during a 90-minute lecture period after the underlying physics of the topics, two source interference and light and shadow, had been covered in the lectures and recitation sessions. The intervention was guided by two trained instructors[19].

At the start of the intervention the students were asked to arrange their seating in every second row of seats in the lecture hall so that the instructors could easily move around and amongst them during the intervention. The students were then requested to respond to the test questions individually and to collaborate with their peers while working on the tutorial tasks. The intervention started with a brief introduction of the topic of the intervention – Two Source Interference or Light and Shadow – with a brief explanation of how students were expected to participate in the intervention. During the remainder of the intervention, the students either worked through the tutorial worksheets or responded to the test-questions displayed on the screen at the front of the lecture hall.

While the students were working on the worksheets, the instructors moved amongst them, monitoring their progress. As suggested by the tutorial developers, the instructors aimed at activating the students' thinking by questioning rather than telling. During the intervention, the students were permitted to use the course textbook and other instructional material.

At the end of the intervention, the students returned the tutorial worksheets and their answer sheets, which were scanned for the subsequent analysis. The worksheets and answer sheets were returned to the students at the end of the following recitation session, and for those who were interested in hearing the correct answers, there was also a brief discussion. The tutorial homework assignments were excluded from the intervention,

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[19] In 2011-2013 the instructors were Mervi A. Asikainen and Mikko Kesonen. In 2014, Mervi A. Asikainen and Risto Leinonen ran the Light and Shadow tutorial, while Mikko Kesonen and Risto Leinonen ran the tutorial focusing on Two Source Interference.

because their impact on the students' learning would have been difficult to evaluate.

6.3 EXPERIMENTAL DESIGN UNDERLYING THE EVALUATION OF STUDENTS' LEARNING IN THE INTERVENTION

The evaluation of the students' learning in sub-study 2 was based on the *pre-experimental one-group pretest-posttest design* (Cresswell, 2009). In general terms, this type of design permits evaluation of the impact of a treatment without the inclusion of a comparison group (Fraenkel & Wallen, 2000). In sub-study 2, dividing the group of students into experimental and comparison groups was not an option due to practical constraints. In consequence, all students undertook the treatment, which included working on the tutorial tasks during the intervention. The impact of this treatment was indicated by testing the students' knowledge before (pretest) and after (posttest) they had worked through the tasks. Testing was accomplished with the aid of paper-and-pencil test questions. The students' learning was evaluated by comparing the proportions of correct and incorrect responses before and after they had worked through the tutorial tasks. We paid attention in this evaluation to the extent to which the students' responses shifted towards the correct line of reasoning after they had worked through the tutorial tasks. This evaluation was used to indicate the impact of the tutorial tasks on their learning[20].

In addition, the intervention permitted evaluation of the level of the students' knowledge after they had gone through the lecture-based instruction. This was possible since the underlying physics had already been covered in the weekly lectures and recitation sessions. Evaluating the students' knowledge after lecture-based instruction corresponds to the *pre-experimental one-shot case study design* (Cresswell, 2009). This means that all of the participants receive the same treatment – lecture-based instruc-

[20] This impact was paralleled by the effectiveness of the intervention.

tion – followed by an assessment – the pretest tasks in the tutorial intervention. This design provided only a little information about the impact of the lecture-based instruction (Fraenkel & Wallen, 2000). However, the design provided a useful indication of the level of the students' knowledge following the lectures and recitation sessions. This indication at least revealed the extent to which students had encountered difficulties after lecture-based instruction similar to those that had motivated the original development of the Two Source Interference and the Light and Shadow tutorials.

Sections 6.4 and 6.5, below, discuss both of the implementations staged in the intervention and highlight some of the pertinent results obtained in 2011-2014.

6.4 STUDENTS' LEARNING ABOUT TWO SOURCE INTERFERENCE

In the implementation of the Two Source Interference tutorial, the tutorial worksheet was divided into four sections[21]. For each section we designed a test question that was posed before (pretest) and after (posttest) students had worked through the tutorial tasks included in a section. Thus, students' learning was evaluated by comparing their pretest and posttest responses given in each section. This sectional evaluation of students' learning captured the extent to which students could improve their responses after working for 5-15 minutes on the tutorial tasks.

The test questions were designed to address the main theme of each section of the tutorial worksheet. The test questions employed representations of the two source interference phenomenon that differed from those used in the lectures, the recitation sessions, or the tutorial tasks. This representation is presented in section 2.4 in Figure 2.3a (p. 17), while the representation used

[21] Section 1: pp. 213-214, tasks II A-C; section 2: pp. 214-216, tasks II D-J; Section 3: pp. 216 tasks III A; Section 4: pp. 217, tasks III B-C (McDermott et al., 2010a)

in earlier instruction and tutorial tasks is presented in Figure 2.3b (p. 17).

The use of different representations was intended to ensure that the students could not provide correct responses merely by memorizing tasks covered previously. The use of different representations seemed appropriate since students typically encounter difficulties in visualizing the phenomenon of two source interference (Knight, 2002). If students could provide a correct response in the context of an unfamiliar representation, they were deemed to possess a good understanding of the two source interference phenomenon.

At the start of the intervention, the representation used in the test questions was briefly introduced by showing a corresponding web-animation[22]. In addition, we informed the students that the animation illustrated the phenomenon of two source interference within the areas of constructive and destructive interference. The introduction of the representation was intended to ensure that the students would be able to understand what was being asked for in the test questions.

The results discussed here concern a second section of the intervention, which focused on the concepts of path-length difference and phase difference by emphasizing its role in determining the lines of complete constructive and destructive interference. In the second section, students worked essentially with the diagram presented in Figure 6.1, where sources were 1.5λ apart and oscillated in phase. In the first section of the intervention, students had labelled the points where the amplitude of the resultant waves was greatest and lowest with respect to the level of equilibrium[23]. At the beginning of the second section, the students responded to the test question presented in Figure 6.2. The question asked them to evaluate the values of the path-length difference and phase difference at three points – labelled A, B,

[22] http://ngsir.netfirms.com/englishhtm/Interference.htm (valid 23.5.2014)

[23] For a more precise description of the tutorial tasks included in the first section of the intervention, see article II.

and C – of an interference pattern. The desired values of the path-length difference were $\Delta r_A = \lambda/2$, $\Delta r_B = 0$, $\Delta r_C = \lambda$.

The interference pattern used in the test-question corresponded to the diagram students had worked with in the first section of the intervention (see Figures 6.1 and 6.2). In the second section, students continued working with the diagram and determined the values of the path length difference and phase difference at the points mentioned in the test question. Thus, the students determined the correct answers to the test question in the context of a different representation while working with the tutorial tasks in the second section of the intervention.

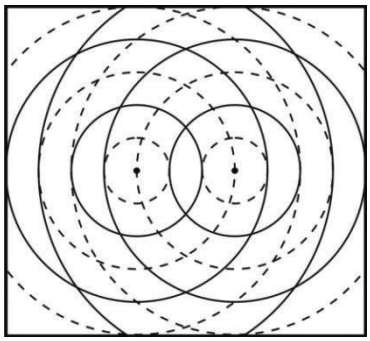

Figure 6.1. *The diagrammatic representation used in the tutorials tasks. The continuous circles represent crests and the dashed circles represent the troughs of waves.*

Estimate the values of the path length difference and phase difference (Δr, Δϕ) at points A, B and C. Express your answer in terms of wavelength and radian.

Explain how you reached this conclusion.

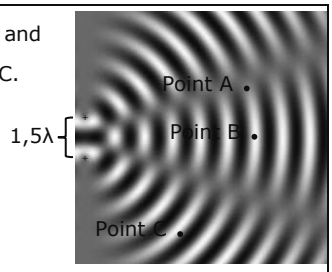

Figure 6.2. *Test question used to indicate students' understanding of the concepts path-length difference and phase difference in the second section of the tutorial intervention covering the topic of two source interference.*

Figure 6.3 presents the proportions of students providing the correct values for the path-length difference at the beginning and end of the second section of the course in 2011-2014. The bars in Figure 6.3 represent the average of the proportions of the students who provided correct answers at the different points – A, B and C in Figure 6.2 – of the interference pattern. The error bars indicate the variation in these proportions in terms of standard deviation.

As can be seen in Figure 6.3, an average of more than half of the students were unable to determine the correct values for the path-length difference before working on the tutorial task. This indicates that after the lecture-based instruction fewer than half of the students were able to apply the concept of path length difference in the context of the novel representation. This implies that the concept of path-length difference is difficult for students to learn, requiring instruction that is more effective than that provided in traditional lectures. This conclusion is consistent with the findings of the developers of the Two Source Interference tutorial (Ambrose et al., 1999; Wosilait, 1996).

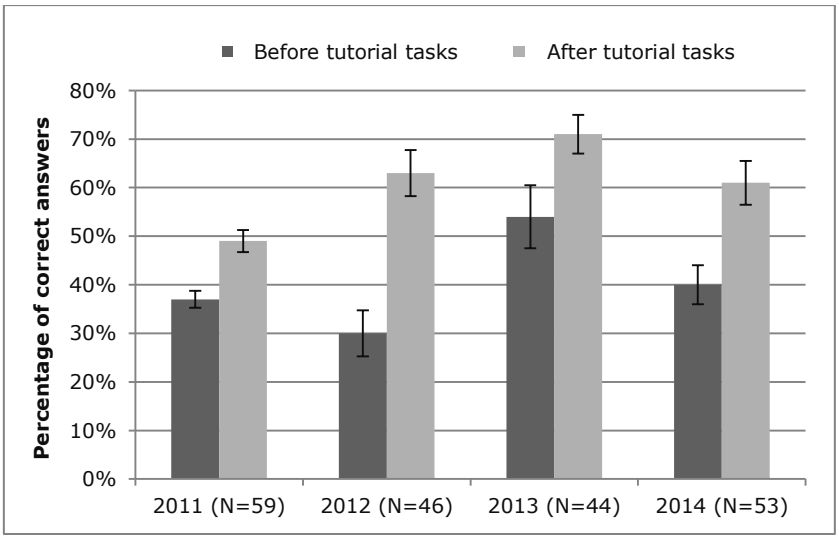

Figure 6.3. *Averages and standard deviations of the percentages of students' correct answers with respect to the values of path-length differences in the second test question (see Figure 6.x1, page 51) used in the tutorial intervention from Two Source Interference. The results obtained in 2011 were published in article II, while the rest of the results are still unpublished.*

Figure 6.3 also shows that the proportions of students' correct responses increased after they had worked through the tutorials tasks. This increase has been evident for four successive years, although the level of the increase has varied noticeably. The error bars in Figure 6.3 suggest that points A, B, and C, labelled in the test question (see Figure 6.2), have not been of equal difficulty for the students. These error bars are not, however, as large as the improvements in the average percentages of students' correct responses. This indicates that the tutorial tasks have helped students to apply the concept of path-length difference to a different representation.

In addition to the improvements observed in the students' correct responses, approximately 30% – 50% of the students failed to provide the correct values for the path-length difference even after working through the tutorial tasks. The most remarkable of the students' misconceptions was that they confused the concepts of path-length and path-length difference. This confusion became evident when the students claimed that the value of the path-length difference corresponded to the distance between the wave sources and a point labelled in the test question. Earlier studies have also recognized this misconception in the context of two source interference (Ambrose et al., 1999; Wosilait, 1996). Hence, this seems to be an obstacle that students are likely to encounter when applying the concept of path-length difference in the case of two source interference. Combining different representations of the two source interference phenomenon might, however, provide a useful starting point for improving students' learning of the concept of path-length difference, as suggested in article II.

6.5 STUDENTS' LEARNING ABOUT LIGHT AND SHADOW

In the case of the Light and Shadow tutorial, students' learning was evaluated with the aid of the pretest-posttest design (Cresswell, 2009). The test questions used were adopted from the Light and Shadow tutorial (Wosilait et al., 1998; Wosilait,

1996). This choice was motivated by an attempt to compare the impact of the tutorial intervention with that of the small classroom implementation of the tutorials. The pretest questions were converted into a multiple-choice format in order to reduce the students' response time and to minimize the number of blank or vague responses.[24] Figure 6.4 presents the pretest question; its alternatives A-E were based on earlier studies, as stated in the following:

- Figure A: a long line source stretches the hole-shape aperture (Wosilait et al., 1998)
- Figure B: the shape of a geometrical image is similar to the shape of a light source (Wosilait et al., 1998).
- Figure C: a correct answer.
- Figure D: the role of an optical component is to invert the image seen on the screen (Saxena, 1991; Goldberg & McDermott, 1987).

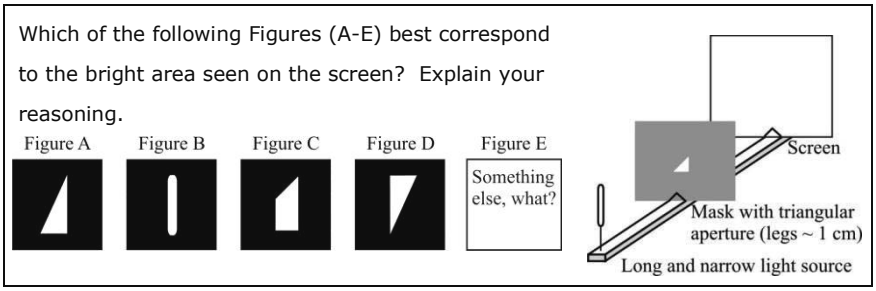

Figure 6.4. *The test question used at the beginning of the tutorial intervention covering the topic of Light and Shadow (Modified from* (Wosilait, Heron, Shaffer, & McDermott, 1998; Wosilait, 1996)).

The Light and Shadow tutorial worksheet consists primarily of tasks that request students to predict geometrical images seen on a screen when different apertures are illuminated using light sources that vary in shape. In addition, students are asked to verify their predictions by undertaking hands-on experiments (Wosilait et al., 1998).

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[24] According to our observations, when responding to unfamiliar questions students provide answers more easily to multiple-choice rather than open-ended questions.

To conduct this type of task in a lecture hall setting, the tutorial worksheet was divided into eight sections[25]. Each section included between two and four predictions, after which the real (correct) geometrical images were demonstrated at the front of the lecture hall. To make the geometrical images visible to the students, the images were displayed on a large screen in the lecture hall with the aid of a web-camera.

After demonstrating the geometrical images, students were asked to compare their prediction with the images seen on the screen. If they were inconsistent, the students were asked to rethink their reasoning.

At the end of the intervention, the students responded to a posttest question, presented in Figure 6.5. The question required students to apply essentially the same procedures as those that were needed for the pretest question (see Figure 6.4). The students needed to divide a line source of light into closely spaced point sources of light and then apply the rectilinear propagation of light. In addition, they were required to notice that each point on a line source created aperture-shaped images next to each other. These images together formed the geometrical image seen on the screen. The students' pretest and posttest answers were compared in order to evaluate the extent to which the Light and Shadow tutorial supported students' learning of the formation of the geometrical image created by a line source of light.

By following the analyzing procedures used by the developers of the Light and Shadow tutorial, the students' responses were placed in three main categories termed as *correct or nearly correct responses*, *misconceptions*, and *others*. The misconception category was divided into subcategories that covered the majority of the students' incorrect responses. Table 6.1 presents the categories and examples of the students' responses embedded in them.

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[25] 1. Part: section I A in pp. 185; 2. part: section I B in pp. 185; 3. part: section I C – D in pp. 185; 4. part: section I E in pp. 186; 5. part: section I E in pp. 186; 6. part: section I F – G in pp. 186; 7. part: section II A-B in pp. 187; part 8: section II C in pp. 187.

Draw the shape of the bright area seen on the screen. Explain verbally and with the aid of a sketch how the bright area is formed. Diffraction can be ignored.

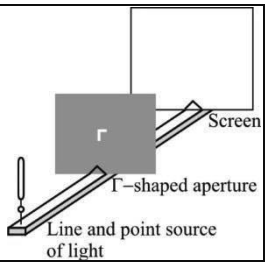

Figure 6.5. *A test question used at the end of the tutorial intervention covering the topic of Light and Shadow (Modified from the references* (Wosilait et al., 1998; Wosilait, 1996))

The students' responses were categorized as correct or nearly correct if they contained a correct geometrical image or an image that corresponded to the shape of the light source. The students' responses belonged to the misconception category if they reflected following ideas: the geometrical image is similar to the aperture; a long light source stretches the image seen on the screen; or the aperture inverts the geometrical image (see Table 6.1). The final main category, termed others, consisted of students' responses that did not fit into the previously described subcategories, such as vague or blank responses.

Table 6.1. *Typical students' responses categorized as correct, nearly correct, or misconceptions.*

Category	Pretest responses	Posttest responses [A]
Correct and nearly correct responses Correct response	 *From every point of the [long] light source, light rays will reach the screen by travelling through the aperture*	 *The light source creates a long image that consists of several Γ-shaped images.*
Nearly correct response: *Geometrical image corresponds to the shape of a light source*	 *The top and bottom of the light source emits rays that travel through the aperture and create an image corresponding to the light source in shape.*	 *The long light source creates a bright line stretching to the screen.*
Misconceptions *The shape of a geometrical image corresponds to that of the aperture*	 *A single light source creates a hole-shaped image on the screen*	 *The light source is like a line. The image is similar [to the aperture], but its size increases*
The long light source stretches the aperture-shaped geometrical image	 *Because the light source is long, the image will be elongated*	 *A long light source elongates a vertical part of the image*
The aperture inverts the image	 *The image turns upside down and elongates*	 *The image is upside down on the screen*

[A] By following the analyzing procedures of the developers of the Light and Shadow tutorial, only the geometrical image created by the long light source was analyzed. In this Table, the geometrical images included in the students' posttest responses have been redrawn for the sake of clarity.

Figure 6.6 presents the proportion of students' responses that were placed in the main categories before (pre) and after (post) they had worked through the Light and Shadow tutorial in 2011-2014. During these years, approximately 30% of students provided a correct or nearly correct geometrical image in the pretest (Figure 6.4) both at the beginning of the intervention and also after lecture-based instruction. A majority of the students, some 60%, were unable to divide a line source of light into closely spaced point sources. Instead, they showed that they possessed misconceptions according to which, for example, a long light source produces an aperture-shaped geometrical image (see Table 6.1). This suggests that the students lacked relevant factual, conceptual, and/or procedural knowledge about the

formation of a geometrical image, although they had previously been lectured on the topic, which had also been covered in the recitation sessions. On the other hand, the students may have been aware of how a geometrical image needs to be formed but they may have lacked certainty about its formation. Instead, they may have considered their intuitive ideas – a long light source stresses a geometrical image – more acceptable. A high proportion of the students using these types of intuitive ideas after the lecture-based instruction were also observed in the previous studies concerned with students' learning about image formation (Wosilait et al., 1998; Saxena, 1991; Goldberg & McDermott, 1987). Thus, sub-study 2 supports the principal message of these studies: lecture-based instruction is an ineffective way to help students to refine their intuitive ideas regarding the desired content knowledge of image formation.

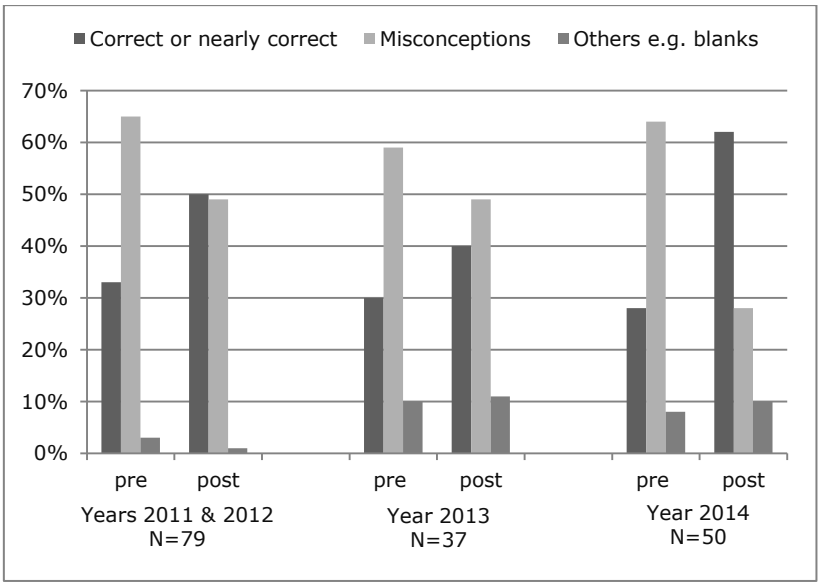

Figure 6.6. *Proportions of categorized students' pretest and posttest answers obtained in 2011-2014. The results from 2011 and 2012 have been published in article III, while the rest of the results are still unpublished.*

Figure 6.6 shows that after students had worked through the tutorial tasks, the proportion of their correct or nearly correct responses increased, while the proportion of misconceptions decreased. These changes continued to be apparent in 2011-2014, although the increase in the proportions of correct responses varied by between 10 and 35 percentage points. The improvements observed in 2011/2012 and in 2014 were statistically significant[26], whereas the improvement observed in 2013 was statistically insignificant[27]. Although the level of statistical significance has varied during 2011-2014, overall the results indicate that students have been able to improve their ability to determine the shape of geometrical images. Improvements in their abilities, in turn, suggest that the intervention has indeed supported students' learning about image formation.

The improvements observed in students' correct and nearly correct answers have been somewhat moderate compared to those obtained by the developers of the Light and Shadow tutorial. The latter have reported improvements of approximately 60 percentage points when students responded to pre- and post-tests that were comparable to those used in the intervention (Wosilait et al., 1998). This improvement is nearly twice as large as our own largest improvement (35 percentage points). Thus, our intervention cannot be considered to have been as effective as the developers' small classroom implementation of the tutorials.

To explain this difference in effectiveness, we have suggested three factors, which will be labelled here as *familiarity*, *the use of the homework assignment*, and *instructional setting*. Familiarity refers to the extent to which the students were familiar with the tutorials. It was our belief that students who have grown accustomed to the tutorials can take better advantage of them than students who face them for the very first time. The developers of the Light and Shadow tutorial typically use the tutorials as weekly bases in their introductory courses at the University of

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[26] Results of the McNemar test: $\chi^2(1) = 5.452, p < 0.05$ (in 2011/2012); $\chi^2(1) = 11.84, p < 0.05$ (in 2014).

[27] Results of the McNemar test: $\chi^2(1) = 0.600, p > 0.05$ (in 2013).

Washington (UW). Thus, their students were more familiar with the tutorials than were our students, who experienced the tutorials for only the second (or even first) time in the Light and Shadow tutorial intervention in 2011-2013. In the academic year of 2014, the tutorials were adapted for use in all of our introductory lecture courses.[28] In this new situation, the students had then experienced several tutorials (max. 9) before participating in the Light and Shadow tutorial intervention. In that year the proportion of students' correct and nearly correct responses improved to a greater degree than in 2011-2013 (see Figure 6.6). This supports our belief that the tutorials are more effective when students have already become familiar with them.

The use of the homework assignment refers to the fact that the homework assignment of the Light and Shadow tutorial was omitted in the intervention. Thus, our students could not have benefited from the homework assignment in the same way as did their counterparts in UW (Wosilait et al., 1998). The absence of the homework assignment may then explain the modest effectiveness of the intervention compared to the small classroom implementation of the Light and Shadow tutorial.

The instructional setting refers to differences in the facilities available in the intervention and the small classroom implementation of the tutorials. During the intervention, students work with their neighbors in a lecture hall while looking at the demonstrations presented by the instructors. In small classroom implementation, students work in small groups and conduct hands-on experiments by themselves while verifying their predictions. In a small classroom, students may test their ideas more flexibly while conducting hands-on experiments than students who are watching the demonstrations in a lecture hall. In addition, in a small classroom implementation the instructor-student ratio is higher than that of the tutorial intervention. In

[28] The use of the tutorials was extended as a part of a more extensive programme aimed at developing the teacher education provided in the Department of Physics and Mathematics at the University of Eastern Finland (http://www.uef.fi/fi/fysmat/-/matematiikan-ja-fysiikan-opettajankoulutuksessa-puhaltavat-uudet-tuulet (valid 3.9.2014)).

consequence, students obtain more assistance in the small classroom implementation than in the intervention. These differences may explain why the intervention was not as effective as the small classroom implementation in the case of the Light and Shadow tutorial.

6.6 SUMMARY OF SUB-STUDY 2

Overall, the sub-study 2 supports the well-known claim that lecture-based instruction is ineffective in overcoming students' misconceptions and difficulties (McDermott, 2001; Redish, 1999; Reif, 1995; Van Heuvelen, 1991). The tutorial intervention designed in sub-study 2 has proved to help students to resolve some of their misconceptions and difficulties. This positive effect on students' learning has not been temporary but appeared almost every year from 2011 to 2014. These findings indicate that the tutorial intervention supports students' learning, and hence it can be considered to be a useful supplement to a conventional lecture-based physics course.

7 Overview of sub-study 3

In sub-study 3 we aimed at understanding why students tend to combine the ray and wave properties of light inappropriately. This tendency of students to do so has been frequently reported in the PER and Science Education –literature (Sengören, 2010; Maurines, 2009; Colin & Viennot, 2001; Ambrose et al., 1999; Wosilait, 1996). This tendency has become evident, for example, when students have predicted that the central maximum of a single-slit diffraction pattern is a geometrical image of a slit created by a light that travels straight through the slit (Ambrose et al., 1999; Wosilait, 1996). Its appearance has suggested that students' are experiencing difficulties in recognizing the validity ranges of the ray model and the wave model of light (Ambrose et al., 1999). In addition, Ambrose, Shaffer, Steinberg, & McDermott, (1999) have suggested that students construct a single model of light known as a *hybrid model of light*. As a result of constructing this hybrid model of light, students fail to understand that light can be described in terms of either rays or waves, depending on the situation.

Maurines (2009) has argued that students' use of the hybrid model of light indicates that their knowledge is not as well organized as might be desired. Colin and Viennot (2001) have suggested that students' unorganized knowledge may be caused by pictorial representations that are commonly used in optics. In such representations a line can represent a light with or without the relevant wave properties of light. Thus, using a line as a unified description of light may lead students to think that a single model will suffice to explain the behaviour of light.

Sub-study 3 has aimed at deepening these earlier contributions by considering the context-dependency of students' inappropriate combinations of the ray and the wave properties of light. We investigated how different light sources explicitly stated in optics task assignments impact on students' reasoning. As

described in section 3.3, students' reasoning is seen as a process in which students shift from their premises towards their conclusions. The context-dependency of this process is explained by assuming that students create mental models or propositional representations concerning their reasoning premises (see section 3.3.2). In sub-study 3, we aimed at identifying the types of premises of reasoning that the students associated with light emitted by a small bulb or a laser. We also attempted to understand whether students' premises relied more on propositional representations than on mental models, or *vice versa*. To detect this distinction, we used principal assumption of Johnson-Laird: the mental models are structural analogies of the world which mimic perceivable features of the world rather than its underlying principles (Johnson-Laird, 1983). In addition, we have used the criteria suggested by Creca and Moreira (1997): a student's reasoning emerges from the mental models if s/he uses qualitative descriptions such as drawings that demonstrate his/her understanding of the situation at hand. A student's reasoning emerges from the propositional representations if s/he merely recalls pieces of information, such as a concept of physics, without being able to apply it in a real-world situation.

In addition to the students' premises of reasoning, we investigated how explicitly the stated light sources in optics task assignments impacted on the conclusions that the students drew as result of their reasoning. To understand the impact of the instruction, the students' reasoning premises and also their conclusions were investigated before and after instruction. Students' reasoning premises were inferred from their explanations, whereas their conclusions were inferred from their predictions. Thus, the students' reasoning premises and conclusions were additionally termed their *assumptions* and *predictions*, respectively. Overall, sub-study 3 aimed at understanding the type of reasoning students use in determining a bright area created by a small bulb or a laser and whether the presence of these light sources could explain why they tend to combine the ray and wave properties inappropriately.

7.1 CASE STUDY DESIGN

The research undertaken in sub-study 3 corresponded to the *case study* (Flyvbjerg, 2011), since we aimed at understanding a single phenomenon in a single context. The phenomenon in question was students' inappropriate combinations of the ray and wave properties of light. The context was the Basic Physics IV course (BP-IV).

BP-IV provides an especially suitable context for sub-study 3, since the course follows the textbook by Knight (2008a). This textbook distinguishes between the validity ranges of the ray model and the wave model of light, as presented in section 2.6. The students participating in the BP-IV course are taught to follow this distinction regardless of the type of light source used in the optics task assignments. This has permitted us to examine how students apply these validity ranges in their reasoning when a small bulb or a laser is used as the light source in optics task assignments. Thus, the *case* in sub-study 3 is students' inappropriate combinations of the ray and wave properties of light in the contexts of a small bulb or a laser observed during the BP-IV course.

In a case study, various data sources are typically used to obtain a comprehensive understanding of a case (Flyvbjerg, 2011). The findings of sub-study 3 are based on students' responses to paper-and-pencil multiple-choice/open-ended test questions, students' interviews, and physics textbooks that the students have probably used at upper and lower secondary school level. The research data gathered from the students consists of (1) their written responses to a pretest held during the first lecture of the BP-IV course (N=152); (2) their interviews conducted about two weeks after the pretest (N=4); and (3) their written responses to a posttest held as part of the course exam (N=54). These data sources were analyzed (1) from the perspective of the context-dependency of the students' reasoning (presented in section 3.4); (2) from the perspective of conceptual models that the students had been taught at earlier stages of their education and during the BP-IV course. The following section briefly pre-

sents the main findings of sub-study 3 and discusses their implications. For a more comprehensive presentation of the results, see article IV.

7.2 MAIN FINDINGS AND DISCUSSION

Students' assumptions about light and its behaviour varied noticeably depending on whether a small bulb or a laser was used as the light source in optics task assignments. In the case of the bulb, students often avoided using the relevant simplifications of the ray model of light. They treated a small bulb as an extended light source rather than as a point source of light. They often assumed that the brightness of light rays emitted by a bulb decreases with distance. As a result of these assumptions, students frequently made incorrect predictions about the shape and size of a geometrical image seen on the screen.

In turn, in the case of the laser students seemed to over-idealize the behaviour of light by overemphasizing its rectilinear propagation. This overemphasis became evident when students argued that laser light does not diffract under the same circumstances as light from a bulb, as shown in the student's response presented in Figure 7.1. This student clearly argued that laser light does not diffract as it passes through a small aperture (diameter 0.015 mm), but if the small bulb were the source of light, the light would diffract strongly. This student's response demonstrates how strongly the presence of a certain light source may impact on students' reasoning about optics.

Because the laser [light] travels rectilinearly, the diffraction does not occur…. If the small point-source-like bulb was used as light source, the light would diffract strongly

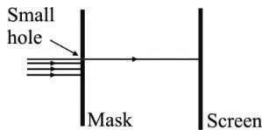

Figure 7.1. *A student's explanation that reveals an overemphasis on the rectilinear propagation of light in the case of a laser.*

The Johnson-Laird mental model theory (1983) has permitted us to understand why students may possess assumptions, in the present case, concerning the small bulb and the laser. The theory suggests that students' assumptions arise from their mental models or propositional representations, which mimic perceptible features of the world rather than its underlying structure. This sheds some light on why students treated the small bulb as an extended light source rather than a point source of light. The perceivable feature of a small bulb is, indeed, an extended light source – a bulb with real dimensions – rather than a point source of light. This is in fact so, since a point source is a physics idealization that does not exist in the real world. Thus, it seems unlikely that the students' would have a mental model of a small bulb that would mimic a point source of light that does not exist in the real world.

In addition, Finnish upper and lower secondary school textbooks typically discuss the creation of shadows in the context of an extended light source.[29] This discussion may have supported the creation of the students' mental model according to which a small bulb behaves as an extended light source. Interestingly, these textbooks also cover a point source idealization of a small bulb, but this detail was rarely used in the students' reasoning. To explain this feature of students' reasoning, the mental model theory (Johnson-Laird, 1983) suggests that the semantic meaning that students grasp from a small bulb refers to an extended light source rather than a point source of light. This implies that when a small bulb is explicitly stated in an optics task assignment, students are likely to think that the bulb refers to an extended light source rather than to a point source of light. Thinking of a small bulb as an extended light source may explain why students provide incorrect responses to optics tasks.

In the case of the laser, a narrow and collimated beam of light is one of the most distinct features of laser light. Thus, this feature may have supported the creation of students' mental model according to which laser light always travels rectilinearly.

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[29] For more information, see article IV.

This type of student mental model would explain why students often assumed and overemphasized the detail that laser light travels rectilinearly, as illustrated in Figure 7.1. This kind of overemphasis was also observed when students evidently recognized the validity ranges of the ray model and the wave model of light. These students correctly predicted that the diffraction pattern would appear on a screen when laser light passes through a small aperture. However, these students argued that the diameter of a central maximum of the diffraction pattern would be equal to the diameter of the aperture. Typically this argument was based on assumptions that the central maximum is created by the portion of the laser beam that travels straight through an aperture. This type of incorrect response corresponds to the use of the hybrid model of light previously reported by Ambrose et al., (1999). In sub-study 3, students' use of this hybrid model seems to be motivated by their assumptions, according to which laser light travels rectilinearly. This differs from the conclusion stated by Ambrose et al., (1999), since they suggested that the hybrid models of light are caused by students' inability to recognize the validity ranges of the ray model and the wave model of light. To develop the idea of the hybrid model of light presented by Ambrose's et al., (1999), we have suggested that the hybrid models of light could be seen as a tendency on the part of students to combine perceptible features of light in a given context. Our suggestion implies that students combine the ray and wave properties of light inappropriately because their reasoning mimics the perceptible features of light. Thus, this perspective broadens the explanations provided by earlier studies about why students tend to combine the ray and wave properties of light inappropriately.

8 Reflections

This final chapter concludes this dissertation by reflecting on the implementation of the study from three perspectives. First, therefore, the underlying assumptions of the present study are discussed. Secondly, the main findings of the sub-studies 1-3 are discussed, and the problems threatening our inferences drawn in sub-studies 1-3 are addressed. And finally, the relevance of the present study is discussed by presenting its implications and ideas for further research.

8.1 UNDEFINED PARADIGM

In Finnish PER and Science Education doctoral dissertations, the underlying assumptions of the research have been defined conventionally in terms of a *paradigm*, such as pragmatism or constructivism (see, e.g., (Leinonen, 2013; Nivalainen, 2011)). The paradigm describes the philosophical stance of a study. Guba and Lincoln (1994) have suggested ontological, epistemological, and methodological questions suitable for determining the paradigm. The ontological questions specify the nature of reality: whether it can be assumed that people construct their own realities or that they exist in a single "real" reality that is committed to in a particular study. The epistemological questions specify the relationship between the knower and what can be known from reality. The methodological questions specify how that knowledge can be obtained from the reality under investigation in a study.

In Finnish PER and Science Education doctoral dissertations the paradigm is often used to justify the selection of data-gathering and analyzing procedures (see, e.g., (Leinonen, 2013; Nivalainen, 2011)). Describing a study in this way implies that a researcher has first defined the paradigm for the study and then

derived everything else from it. This type of process does not, however, describe what has happened in the present study: the underlying assumptions of sub-studies 1-3 have mainly been implicit throughout the research process. As a consequence, the underlying assumptions have varied amongst those sub-studies.

In sub-studies 1 and 2, students' knowledge is assumed to emerge from a reality that is real and not constructed by the researcher. To obtain information from this reality, test questions were designed to investigate students' knowledge. In sub-study 1 the test questions were used in the form of a cross-sectional survey, while in sub-study 2 they were used in the form of a single group pretest-posttest experimental design. Both studies were assumed to provide information on the recurrent and predictable patterns of students' knowledge existing within a given real reality. In sub-study 1 the recurrent pattern of the students' knowledge was their failure to apply the interrelationships of the electric and magnetic fields. In sub-study 2, the recurrent pattern was the increase in the proportion of students' correct answers after working through the tutorial tasks. Overall, the underlying assumptions of sub-studies 1 and 2 correspond closely to *(post)positivism* (Teddlie & Tashakkori, 2009; Guba & Lincolm, 1994).

In sub-study 3, students' responses started to make sense after they were looked at from the perspective of the Johnson-Laird mental model theory (Johnson-Laird, 1983). In other words, the meaning of students' responses was constructed with the aid of that theory. Thus, in sub-study 3, students' knowledge and reasoning were assumed to emerge from a reality that was constructed by researchers. We interpreted the meaning of students' responses by contrasting them to the mental model theory and other available data sources, such as lower and upper secondary school textbooks. Hence, the underlying assumptions of sub-study 3 closely correspond to *constructivism* (Teddlie & Tashakkori, 2009; Guba & Lincolm, 1994).

As the analysis presented above implies, the present study is difficult to position under a single paradigm. One could suggest that the present study comes under *pragmatism*, thus permitting

the underlying assumptions of the study to vary. Pragmatism also emphasizes a commitment to assumptions that work for a given study. (Cresswell, 2009; Teddlie & Tashakkori, 2009) But since I have not consciously committed to this paradigm at any phase of this study, I do *not* wish to locate my work under pragmatism. Rather, I would argue that the paradigm of the present study remains *undefined*. The underlying assumptions of this study have been based mainly on the PER literature, which I have actively followed in the course of the research process. In this literature, the paradigm has gained the attention of researchers only quite recently (see (Robertson, Scherr, & McKagen, 2013)). This may explain why I have not paid attention to the paradigm of the present study during its early stages.

8.2 MAIN CONTRIBUTIONS

The contributions made by the present study arise in particular from those of the sub-studies, which are summarized below.

Sub-study 1 focused on students' learning about the electromagnetic nature of light. As its main contribution, it has demonstrated students' difficulty in applying the interrelationships of the electric and magnetic fields in various contexts. To address this student difficulty, the implications for teaching electromagnetism and optics have been presented in article I. We have suggested that the difficulty and its implications that have been identified would provide a useful foundation for further development of instruction in the fields of electromagnetism and optics.

Sub-study 2 focused on the adaptation and adoption of the Tutorial in Introductory Physics curriculum (McDermott et al., 2010a). The main contribution of sub-study 2 has been the tutorial intervention, which permits the adaptation of the tutorials for use in a lecture hall setting, where their impact on students' learning can be tested without large changes being made to a conventional physics course. In addition, sub-study 2 has shown that the intervention has had a positive impact on students'

learning about the basics of the ray model and the wave model of light. Overall, therefore, the sub-study 2 has broadened the use of the tutorials and shown that the tutorial intervention can be regarded as a useful supplement to a conventional lecture-based physics course.

Sub-study 3, for its part, focused on how the light sources explicitly labelled in the optics task assignment influence students' reasoning. The study shows that students' knowledge concerning light and its behaviour may notably depend on the light source used in a task assignment. This indicates, in turn, that students' reasoning in optics probably depends on contexts where reasoning is performed. Hence, students' knowledge of optics should not be evaluated independently of its contextual features, such as the explicitly stated light sources. Sub-study 3 has also highlighted the possibility of extending the resource-based framework (Hammer, 2000) of students' reasoning by means of the Johnson-Laird mental model theory (Johnson-Laird, 1983). We have argued that an extension of this kind could increase the applicability of the framework.

8.3 INFERENCE THREATS

To evaluate the true value of our contributions, the problems threatening our inferences based on these contributions need to be addressed and clarified (Teddlie & Tashakkori, 2009). The term *legitimation*[30] suggests several perspectives that may be used to cover the problems threatening the inferences based on mixed-methods research (Onwuegbuzie & Johnson, 2006). In subsection 8.3.1, which follows, the perspectives proposed by Onwuegbuzie and Johnson (2006) are applied to address the inference threats that are common to all of the present sub-studies. Subsections 8.3.2, 8.2.3, and 8.2.4 specify the legitimation types

[30] *Legitimation* synthesizes the perspectives established for considering the trustworthiness and validity of the qualitative and quantitative inferences, respectively (Teddlie & Tashakkori, 2009; Onwuegbuzie & Johnson, 2006).

that have become a matter of concern in sub-studies 1-3, respectively.

8.3.1 Legitimation types common to all of the sub-studies

Weakness minimization legitimation refers to the extent to which different methods used in a study compensate for their weaknesses (Onwuegbuzie & Johnson, 2006). In the present study, this legitimation type has been dealt with by combining the qualitative and quantitative data sources in all of the sub-studies. Typically, these combinations took the form of test questions that consisted of a multiple-choice part and an open-ended explanation part. The multiple-choice questions revealed the students' overall response distribution, providing, however, little information on the students' knowledge and reasoning underlying their selections. The students' open-ended explanations shed more light on their knowledge and reasoning that underlay the selections that they made in answer to the multiple-choice questions, compensating for their weakness.

Conversion legitimation refers to the quality of inferences made after qualitizing the quantitative data and/or quantizing the qualitative data (Onwuegbuzie & Johnson, 2006). This legitimation type is related to all of the sub-studies, since in all of them the students' open-ended explanations/responses were categorized and presented in quantitative form. This quantitative form is then used to make further inferences about the students' learning of optics. To ensure the high quality of these inferences, the quantizing process has been described extensively in the result sections of articles I-IV. We have presented authentic students' responses and provided explications of what has been interpreted from them. In addition, most of our interpretation and inferences have proved to be consistent with earlier studies. This indicates that they have captured the relevant features of the students' learning about optics and have not simply arisen from the quantizing process.

Inside-outside legitimation refers to how "objectively"[31] a researcher has interpreted the data (Onwuegbuzie & Johnson, 2006). The objectivity of our interpretations has mainly been addressed by describing the logic of these interpretations and their underlying evidence thoroughly. These descriptions are intended to clarify the decisions being made in the analysis of the students' responses presented to the reader. By means of these descriptions, the reader may further evaluate the objectivity and the overall quality of our inferences from his/her own perspectives. In addition to these descriptions, articles I-IV have been subjected to the peer-review process. In that process, the objectivity of our inferences has been evaluated in detail.

In addition to the objectivity of the researcher's interpretations, the inside-outside legitimation concerns the extent to which the informants participating in a study may share a researcher's interpretation (Onwuegbuzie & Johnson, 2006). This type of evaluation was omitted from the present study. The students would probably not have possessed sufficient background knowledge to evaluate the inferences being made concerning their learning.

The *validity* of our test questions – concerning whether they have actually measured what we have assumed that they should measure – may be considered to threaten the objectivity of our inferences. The test questions have been based on tasks presented in peer-reviewed articles and in widely acknowledged textbooks. Thus, the basis of our test questions can be considered valid. With respect to the modifications that we have made to these questions, two experts have evaluated their draft versions. These drafts have been refined until both experts have agreed that they were suitable for the students participating in the present study.

Commensurability legitimation refers to the value of combining quantitative and qualitative data sources. The concept asks whether data sources that have been combined create a view-

[31] Here, objectivity refers to an outsider's (etic) viewpoint that aims at remaining unbiased and hence trustworthy (Onwuegbuzie & Johnson, 2006).

point that goes beyond the perspectives provided by quantitative or qualitative data sources alone. (Onwuegbuzie & Johnson, 2006) The inferences made in sub-studies 1-3 would probably be unobtainable by merely relying on the quantitative data sources alone. This is the case since well-established quantitative instruments (e.g., conceptual surveys) related to the topics covered in sub-studies 1-3 were somewhat hard to find when the data gathering was being planned. On the other hand, if we had used qualitative data sources alone, it would have been difficult to obtain an overview of the students' responses. Without these overviews, it would have been difficult to evaluate the students' learning in the tutorial intervention, for example. Thus, it seems that the inferences being made in the present study have needed the quantitative and qualitative data sources to be combined. Thus, the inferences made in the present study go beyond those could have been made by simply relying on qualitative or quantitative data sources alone.

Multiple validities legitimation refers to the extent to which the best possible research designs have been used preceding the researcher's inference (Onwuegbuzie & Johnson, 2006). This legitimation type is covered in the following subsections, 8.3.2-8.3.4, sub-study by sub-study. In addition, the other actions used to support the inferences made in sub-studies 1-3 are presented in the following subsections.

8.3.2 Additional legitimations of sub-study 1

In sub-study 1, a cross-sectional survey was used to discover the students' conceptions of the electric and magnetic fields and their interrelationships. The survey showed that a noticeable proportion of the students being taught were unable to recognize the interrelationships of the electric and magnetic fields in a number of different contexts. This evidence was sufficient for us to infer that the interrelationships of the electric and magnetic fields is a difficult topic for students to learn, and more studies are needed to reconcile this difficulty. This inference was in line with previous studies, which had demonstrated similar student difficulties with the topics of electromagnetism and physical op-

tics (Ambrose et al., 1999; Furiò & Guisasola, 1998; Bango & Eylon, 1997).

In sub-study 1, researcher triangulation was used to support the objectivity of our inferences. The triangulation was considered essential due to the small sample size (N=33). This was the case since even one inaccurately categorized student's response would have made a substantial difference to the overall students' response distribution. In sub-study 1, the triangulation resulted to refinements of the category descriptions of the students' responses and also to the re-categorization of individual students' responses.

8.3.3 Additional legitimations of sub-study 2

In sub-study 2, the one-group pretest-posttest design was used to evaluate the effectiveness of the tutorial intervention. The following validity threats are related to this design: history, maturation, instrumentation, statistical regression, and mortality (Sheskin, 2003). History refers to the possibility that anything other than an independent variable will cause an observable impact on a dependent variable (Sheskin, 2003). This threat becomes more relevant when the time interval between the pretest and posttest is long. In sub-study 2, the time interval varied by between 10 and 75 minutes. During this time period the students worked on tutorial tasks (an independent variable) in a controlled lecture hall setting under the guidance of two instructors. Thus, it seems unlikely that students' improvements in the test questions (a dependent variable) could have been caused by any other variables than the tutorial tasks that they had undertaken between the pretest and posttest.

Maturation refers to the possibility that any natural learning[32] on the part of the students that occurred between the pretest and posttest would have explained the observed improvements in the students' test responses (Sheskin, 2003). The PER literature has shown that physics in general, and optics in particular, are demanding subjects to learn (McDermott, 2001).

[32] Students' learning that occurs spontaneously, with no external guidance.

Thus, it seems unlikely that maturation would explain the improvements observed in the students' test responses after they had worked through the tutorial tasks.

Instrumentation refers to the possibility that differences in the pretest and posttest tests would explain the observed impact of a treatment rather than the treatment itself (Sheskin, 2003). In the case of the Two Source Interference tutorial, the pretest and posttest questions were identical. Thus, the students had already seen the posttest questions in the pretest phase, which may have helped them to provide better responses to the posttest. Thus, in the case of the Two Source Interference tutorial, the instrumentation may explain some of students' learning outcomes.

In the case of the Light and Shadow tutorial the pretest and posttest questions were different. According to the developers of the Light and Shadow tutorial, the posttest question was at least as difficult as the pretest one (Wosilait et al., 1998; Wosilait, 1996). Thus, in the case of the Light and Shadow tutorial intervention, the students' learning outcomes are unlikely to have been biased by the instrumentation.

Statistical regression refers to the fact that people who provide either very low or very high scores in a pretest tend to approach the mean value of scores in a posttest due either to their luck or to careless mistakes (Sheskin, 2003). In both interventions, the pretest and posttest were designed so that students would be unlikely to provide correct or incorrect responses as a result of simply luck or carelessness. For example, the multiple-choice questions contained four or more alternatives that clearly differed from each other. This reduced the possibility that statistical regression would explain the improvements observed in students' responses.

Mortality refers to the bias that may occur if pretest and posttest samples noticeably differ from each other (Sheskin, 2003). In the case of the Light and Shadow tutorial intervention, we used the McNemar test to evaluate the impact of the tutorial tasks on students' learning. The McNemar test took into account only those students who had responded to the pretest and post-

test. Thus, the pretest and posttest samples have been the same in the case of the Light and Shadow tutorial intervention.

In the case of the Two Source Inference tutorial intervention, the students' pretest and posttest responses were not treated as matching pairs. Consequently, some students may have responded only to the pretest or to the posttest. Thus, we have not ruled out the possibility that mortality would explain some of the students' learning outcomes in the case of the Two Source Interference tutorial intervention.

Overall, the validity threats associated with the one-group pretest-posttest design are addressed to some extent in both interventions, although more comprehensively in the case of the Light and Shadow tutorial intervention than that concerned with Two Source Interference. Despite this difference, the results obtained from both interventions indicate that they supported students' learning of the basics of the ray model and the wave model of light.

8.3.4 Additional legitimations of sub-study 3

In sub-study 3 the design of the case study was mainly adjusted to the acquisition of an understanding of how explicitly stated light sources influenced students' reasoning in optics. The design of the case study permitted us to combine different data sets and to interpret them subjectively from the perspective of the Johnson-Laird mental model theory (Johnson-Laird, 1983). These research actions played an essential role in discovering the main findings of sub-study 3. Thus, the case study design can be considered appropriate for sub-study 3.

Sample integration legitimation is also related to sub-study 3. This legitimation type refers to the threat that emerges if a subset of a sample does not represent the main sample as efficiently as expected (Onwuegbuzie & Johnson, 2006). In sub-study 3, four students selected from the cohort of 152 students[33] were interviewed in order to deepen our understanding of the main findings of the pretest. To avoid any bias being caused by this

[33] The majority of the students was, indeed, requested to give interviews but most of them declined.

small sub-sample, the interviewees were chosen so that their responses demonstrated the main findings of sub-study 3. Thus, they represented the main sample with respect to the students' pretest responses.

Two out of four interviewees were eventually excluded from the final analysis. One of them was not informative when responding to most of the interview questions, resorting frequently to: "*I don't know*". The other was a mature student who had been involved previously in optics research. Thus, his expertise in optics was obviously greater than students typically possess after lower and upper secondary school education. He did not represent the rest of the students and, therefore, he was excluded from the analysis.

8.4 CONCLUSION, RELEVANCE, AND PROSPECT

The relevance of this study rises from the findings and implications of sub-studies 1-3. The relevance of sub-study 1 has been mainly practical. It has indicated that conventional lecture-based instruction is inadequate for ensuring that students' learning about the interrelationships of the electric and magnetic fields will be adequate. In addition, in the case of sub-study 1, we have suggested the implications of supporting students' learning about the interrelationships in the contexts of electromagnetism and optics. These implications may serve as a starting point for the development of instruction whose aim will be to improve students' understanding the interrelationships of electric and magnetic fields. This type of instruction may be useful for implementing in a course where the history of physics is emphasized. The instruction could be tied to one of the most significant historical events of physics: the integration of electromagnetism and optics. The consequences of these historical events could help students to realize the importance of the interrelationships of the electric and magnetic fields. This could further support their learning about these interrelationships and also improve their understanding of the electromagnetic nature of light.

The relevance of sub-study 2 has been mainly practical. It has provided the tutorial intervention, which offers a fairly easy method of testing the effectiveness of the Tutorials in Introductory Physics curriculum (McDermott et al., 2010a) in a conventional lecture-based physics course. In addition, it has shown that the intervention may improve students' learning of the basics of the ray model and the wave model of light. In sum, it could be regarded as a useful supplement in a conventional lecture-based physics course.

Kryjevskaia, Boudreaux, and Heins (2014) have also recently reported on the use of tutorials in a lecture hall setting. They have developed *tutorial-based lectures*, which consist of students working on their tutorial tasks, a whole-class discussion guided by a lecturer, and testing students' knowledge using a single pretest at the beginning and end of a lecture period. It has been claimed that tutorial-based lectures are as effective as their small classroom implementation as tutorials at the University of Washington (Kryjevskaia, Boudreaux, & Heins, 2014). Thus, tutorial-based lectures are more effective than our tutorial intervention. However, they include whole-class discussion, which can be difficult to perform, especially if the lecturer is primarily accustomed to conventional lecturing (Turpen & Finkelstein, 2009; Fagen et al., 2002).

Overall, our tutorial intervention and the tutorial-based lectures can be seen as an attempt to broaden the use of research-based instructional solutions developed in PER. This type of attempt may increase the use of tutorials and thus widening the use of research-based instructional practices in physics teaching.

It would be interesting to consider in the future whether the use of tutorials could better be integrated into physics teacher education. For example, teacher students could work as instructors during the tutorial sessions as a part of their advanced-level teacher studies. During their training, students would work through the tutorial worksheet that is going to be covered in the tutorial session where they might soon be working as instructors. In addition, during their training sessions the students could be informed about the most common students' difficulties

in learning one of the topics of physics covered in the tutorial sessions. Moreover, they could be offered strategies for addressing students' difficulties in teaching by questioning rather than by telling. Working as instructors, teacher students could obtain a personal experience of students' difficulties and how to address them while still intending to teach by questioning. These experiences may support teacher students' commitment to more student-centred ways of teaching, communicating, and encountering their students in the future. Findings in Finland indicate that science teachers seem still to rely on an authoritative teacher-centred style of teaching (Lehesvuori, 2013). To change this tradition, teacher education where teaching by questioning has been made explicit for teacher students could be useful. Thus, integrating the tutorials with physics teacher education could open up new opportunities to improve teacher education both in Finland and also elsewhere.

Sub-study 3 has theoretical, methodological, and practical relevance. It demonstrates the possibility of extending the resource-based framework of students' reasoning (Hammer et al., 2005) by adopting ideas from the Johnson-Laird mental model theory (Johnson-Laird, 1983). This extension could broaden the use of the framework by offering new alternatives for identifying conceptual resources. This possibility has been recognized by one of the peer-reviewers of article IV, which recommends the adoption of Johnson-Laird's findings to the resource-based framework.

In sub-study 3 we found that students may have difficulty in applying a point source idealization in the case of a small bulb. This difficulty seemed to emerge from students' restricted ability to grasp the semantic meaning of a small bulb: they thought that small bulb refers to a real bulb (extended light source) rather than a point source of light. In general terms, students may grasp the semantic meanings of expressions, figures, or symbols used in physics tasks assignments in ways that differ from what was intended. Differences in grasping the semantics – where the expressions, figures, or symbols actually refer to real life – may result in students and experts are not considering the same

thing in the same way. This may reduce the validity of a test question and lead to invalid inferences about students' knowledge and their learning.

However, expert evaluation seems to be a widely accepted way of supporting the validity of novel test questions in the field of PER. The development of different ways of supporting the validity of test questions (and their translations) could be useful at some point in the future. Discovering such ways would be useful for further studies in PER but also for the possibility of using PER-based instructional solutions that typically emphasize teaching by questioning study (Meltzer & Thornton, 2012; Beatty et al., 2006; Meltzer & Manivannan, 2002).

The practical relevance of sub-study 3 is that it also offers another perspective on understanding why students tend to combine the ray and wave properties of light inappropriately. This perspective suggests that students' inappropriate combinations are a consequence of their tendency to reason according to the perceptible features of light and its sources. This perspective explains why drawing a clearer line between the validity ranges of the ray model and wave model of light would not prevent students from combining the ray and wave properties of light inappropriately. Development of instruction that would address the students' reasoning that corresponds to the perceptible features of light would appear to be an essential topic for future research.

Overall, it can be claimed that the present study will have practical, methodological, and theoretical implications for students' learning about optics at university.

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Mikko Kesonen

Improving students' learning about optics at university

This thesis considers university students' learning about optics through investigating students' ideas regarding the basics of the ray model and wave model of light. In addition, the thesis presents a tutorial-intervention aimed at improving students' learning and evaluates its impact. Finally, this thesis discusses the implications that may improve students' learning of optics.

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