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Introducing Special Relativity in Secondary Education

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Introducing Special Relativity in Secondary Education

F. Kamphorst

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Introducing Special Relativity in Secondary Education

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Table of Contents

Chapter 1

Introduction

1.1. Introduction

We all anticipated the Friday lecture in my first week at university. After introductory activities and courses in computer modelling and mathematics we finally got what we came for: A physics course. With a cheery “as is easy to see” the lecturer produced blackboards full of equations and incomprehensible diagrams. This was my first encounter with Special Relativity Theory. Unfortunately, the focus on mathematical formalism in the course contributed little to my understanding of the conceptual content of the theory. To find meaning and gain insight in what Special Relativity was about remained an individual quest.

This quest started two years before, in the hours after the last physics class of the week. With a small group we stayed behind and expanded our understanding of the universe by discussing fascinating physics topics such as relativity theory. Our fascination was not misplaced. Special Relativity Theory (SRT) is one of the iconic theories of physics and prototypical of how new knowledge is developed in this field. It is therefore desirable that secondary students also get acquainted with this theory.

SRT was introduced in the Dutch pre-university level secondary physics curriculum as an elective topic in 2013, as part of a big curriculum reform for students of age 16-18. The aim of this reform was among others that students learned to see the connection between the big discoveries in physics and astronomy and important innovations in society. Another aim was for students to get acquainted with the scientific way of thinking as a human activity and the contributions of this way of thinking to our culture (Commissie Vernieuwing Natuurkundeonderwijs, 2006).

When I started working as a physics teacher the teaching community was in full preparation for this new curriculum. My colleagues and I struggled with the question how to teach these new curriculum topics to our students. In secondary school a formal approach seemed even more misplaced than that first physics course I followed at university. Not all secondary students will have the mathematical tools to build an understanding from such an introduction. It was this formal introduction that was repeated in various ways, in the teacher professionalization courses I attended. Leaving me with the big question: How can I help my students to gain a conceptual understanding of relativity?

It was this desire to improve and expand my tools to teach relativity, that inspired this research project. That we were at a loss how to teach relativity can partly be described to the limited research literature on teaching and learning

Special Relativity (see for instance Dimitriadi & Halkia, 2012; Dimitriadi & Halkia, 2010; Levrini & DiSessa, 2008; Scherr, Shaffer, & Vokos, 2001; Scherr, Shaffer, & Vokos, 2002). Therefore, the aim of this research project is to contribute to the scientific knowledge base of learning SRT in secondary education through the design and evaluation of a teaching and learning sequence.

1.1.1. Brief introduction to Special Relativity Theory

Special Relativity is derived from two postulates with the aim to expand Galilean's relativity principle to the domains of electromagnetism and optics. These two postulates are the Relativity principle, which states that the laws of nature are the same in all inertial frames, and the light postulate. The light postulate states that *"light propagates in empty space with a definite velocity c which is independent of the state of motion of the emitting body"* (Einstein, 1905/1952a, p. 37).

The far-reaching consequences of these two postulates and the theory derived from it involve that space and time, in classical physics regarded as two entities that do not influence each other, are combined in one unified spacetime. Even more, this spacetime is observer dependent. Therefore, everything is described in terms of events: coordinates in spacetime with a specific time and spatial component. The observer dependence of spacetime means that the position and time of events depend on the reference frame they are observed from. Even more, that events that are simultaneous in one frame are not in another. This phenomenon is called the relativity of simultaneity.

Other relativistic phenomena are time dilation and length contraction. Time dilation is the phenomenon that the duration of the time interval between two events depends on reference frame. The time interval is shortest in the proper or rest frame of the events. When the time interval between the same events is measured from a different frame it is longer. With length the opposite happens. The distance between two events in a rest frame is longest. When the distance between the same events is measured relative to a different frame the length is shortened in the direction of the velocity between the frames. The extent to which these phenomena occur depends on the speed between the reference frames.

The Dutch secondary curriculum for pre-university upper-level physics education formulates the following learning aim for SRT: *"The candidate can explain the phenomena of time dilation and length contraction, using the concepts of light speed, reference frame and simultaneity, in the contexts of* *thought experiments and applications"* (College voor Toetsen en Examens, 2018, p. 32). It is noteworthy that the central postulates are not explicitly mentioned in this curriculum goal although it is difficult to attain this learning aim without introducing them. The Dutch curriculum, like most other secondary curricula that also include SRT, is limited to the kinematic part of the theory. However, Special Relativity is an elaborate theory that also encompasses the domain of electromagnetism as well as other relativistic phenomena such as the mass-energy equivalence.

Relativistic phenomena such as time dilation and length contraction only become apparent when the same events are described relative to two reference frames. This makes them inherently different from other physical phenomena that students have encountered in their daily lives or education. This also makes them notoriously difficult to learn. In addition, the fact that relativistic phenomena only become apparent with high relative speeds or a preciseness of observations that are not encountered in daily life, makes that students lack life world experience with these phenomena and that the phenomena are often experienced as counter intuitive.

1.2. Research approach

The aim of our research project is to contribute to educational practice as well as the scientific knowledge base of SRT. A design research (DR) approach supports this dual aim. Design research aims to solve educational problems by designing new educational solutions that work in the "messy" setting in which day to day education takes place. To this end, educators who use this framework not only want to know *if* an educational solution works but also *why* it works (Bakker, 2018, pp. 3-18). A design research approach results in new learning resources (the design) and a local theory that describes if and how the design works, thus meeting the dual aim of contributing to both science and education.

In design research approaches an educational design is tested and improved over multiple design cycles. A characteristic feature of DR is that experts and/or practitioners are consulted to contribute to the design and its improvement. For our research topic, Special Relativity in secondary schools, it was problematic to involve experts in contributing to the initial design since it was the lack of expert knowledge in teaching this subject that inspired this research project. Therefore, we additionally draw on the Model of Educational Reconstruction (MER; Duit, Gropengiesser, Kattmann, Komorek, & Parchmann, 2012; Kattmann, Duit, Gropengiesser, & Komorek, 1996), another framework that offers a design-oriented research approach, to propose the first version of the educational design.

The rationale behind MER is that *“science subject matter issues as well as student learning needs and capabilities have to be given equal attention in attempts to improve the quality of teaching and learning”* (Duit et al., 2012, p. 13). To that end, MER offers a framework in which the educational design is informed by both the analysis of the science theory and its history, as well as the analysis of the learners’ perspective. The holistic approach of MER serves as a useful and flexible tool to scrutinize the educational relevance of learning domains that have not entered mainstream science education yet. Eventually, methods of MER result in an educational reconstruction of a learning domain that contains a content structure for instruction, learning resources, and findings on student perspectives.

1.2.1. Research outline

In this project we will draw on the Model of Educational Reconstruction (MER) as an approach to design a Teaching and Learning Sequence (TLS) in which students can experience the prototypical thinking and reasoning that introduced the concepts of Special Relativity. We developed a reasoning tool, the Event Diagram, to elicit and support students in relativistic reasoning activities (**Chapter 2**) and used this tool to elicit students’ pre-instructional reasoning with light propagation (**Chapter 3**). These pre-instructional models were taken as a starting point for instruction in designing the TLS. A first experimental exploration in small groups offered a detailed understanding of the instructional power of the TLS under optimal conditions (**Chapter 4**). However, the design was not yet suitable to use directly in the classroom. To adapt the design[1] for this context, we involved teachers as co-designers, informed by the DR framework (**Chapter 5**). Figure 1.1 shows an overview of the studies and their place in the overall research project. We will now continue to discuss the outline of this thesis.

[1] The teaching materials are published at https://www.fisme.science.uu.nl/toepassingen/28984/

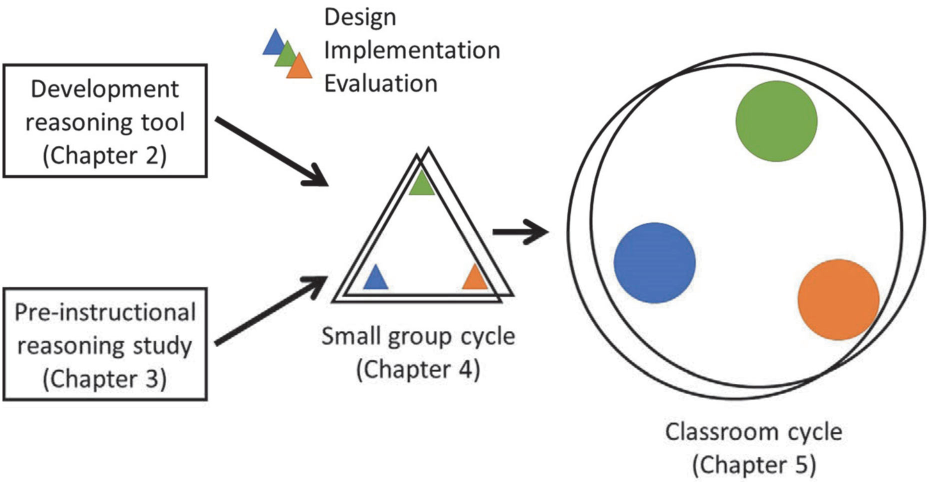

Figure 1.1 Overview of the study design and chapters of the dissertation

In **Chapter 2** we present the Event Diagram (ED) as a tool to support student reasoning with light propagation when they perform relativistic thought experiments. Thought experiments play an important role for SRT, both at the genesis of the theory and in its communication to a wider audience. In a thought experiment the consequences of a theoretical principle are derived in a reasoning activity that is performed in the mind. In relativistic thought experiments this central principle is often the light postulate. It is difficult to perform such a thought experiment for novice learners while reasoning with a new and counterintuitive principle. At the same time, it is also desirable that this reasoning is made explicit and visible for research purposes. EDs can meet these needs: They are representations of spacetime that visualize the context of the thought experiment and in which students can reason with light propagation through drawing.

In **Chapter 3**, we describe how we used EDs to study student reasoning with light propagation prior to instruction. This answers the following research question:

> *RQ 1: Using Event Diagrams, in what ways do secondary education students reason with light propagation in relativistic situations prior to instruction?*

In **Chapter 4** we present an Educational Reconstruction of SRT. To introduce relativistic reasoning with the light postulate, education should build on students' pre-existing ideas on light propagation. The students' ideas described Chapter 3 formed the starting point to design an intervention which introduces the light postulate to secondary students. This intervention aimed at helping students to bridge the gap between their pre-instructional ideas and physics concepts, and aimed at acquainting them with the process of knowledge development as portrayed in SRT. Based on an analysis of the theory and the learning difficulties associated with SRT as reported in the research literature, we proposed a content structure of SRT for instruction. The content structure for instruction was translated in an intervention. The tasks and the aspired student learning are presented in a hypothetical learning trajectory (HLT) in which we describe what we expect the students to do and say when working with the teaching materials. The HLT was evaluated with small groups of students, answering the following research question and sub-research questions:

> *RQ 2: How can learners in secondary education develop a conceptual understanding of SRT through engaging in a process of physics theory development?*
>
> *RQ 2a: How can the key ideas and theory development of SRT be reconstructed into a content structure for instruction?*
>
> *RQ 2b: To what extent can a teaching and learning sequence (TLS) based on the aforementioned content structure be successful in bridging student ideas and physics concepts?*

In **Chapter 5** we present the redesign and evaluation of the TLS presented in Chapter 4 for the classroom. In this way, we address the overall aim of this research project to contribute to SRT learning in secondary schools. The adaptation of the design was done in close collaboration with a group of teachers as co-designers. The design is evaluated on two aspects. First, we address to what extent the intended learning is achieved. Second, we compare the learning outcomes obtained with this intervention to those obtained with regular schoolbooks. The following research questions are answered:

> *RQ 3a: How can the small group TLS be adapted for the classroom context?*
>
> *RQ 3b: To what extent is the intended learning achieved with the classroom TLS?*
>
> *RQ 3c: How do learning outcomes with the classroom TLS compare to those of traditional teaching approaches?*

The overall implications of the research project are discussed in **Chapter 6**.

Chapter 2

Event Diagrams – Supporting Student Reasoning in Special Relativity Thought Experiments

Kamphorst, F., Savelsbergh, E., Vollebregt, M., & van Joolingen, W. (2021a). Event diagrams - Supporting student reasoning in special relativity thought experiments. In D. Blair & M. Kersting (Eds.), *Teaching Einsteinian physics in schools*. New York, NY: Routledge.

Abstract – Thought experiments and drawing diagrams are promising tools to help students obtain a deeper understanding of physical concepts that are hard to imagine. This chapter presents the Event Diagram as a representation of spacetime that allows students to visualize the position of objects and events in Special Relativity Theory. With slight modifications, the Event Diagram becomes not only a representation of spacetime but also a reasoning tool that can support students to perform thought experiments themselves.

Keywords – Special Relativity Theory, Thought Experiments, Event Diagrams, Reasoning

"If I pursue a beam of light with the velocity c (velocity of light in a vacuum)," what would I observe?, wondered Einstein at the age of sixteen. *"I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest. However, there seems to be no such thing, whether on the basis of experience or according to Maxwell's equations"* (Einstein, 1949, p. 53). This simple question and its paradoxical answer revolutionized how physicists look at the world. The mental exploration of this thought experiment eventually led Einstein to propose the light postulate, one of the basic principles of Special Relativity Theory. Special Relativity describes how space and time can no longer be understood as two separate concepts but are one unified spacetime. Even more, how this spacetime is observer dependent.

Nowadays, Special Relativity is finding its way into secondary education, and it would be desirable that some of its revolutionary feeling would be retained in the secondary classroom. To this end students need to gain an understanding of the relativity of simultaneity, time dilation and length contraction. In addition, students need to understand how these phenomena relate to the basic principles of the theory: Light propagation and observer dependence.

It is difficult to gain an understanding of these relativistic phenomena for three reasons. First, the phenomena only emerge if the same observation is described relative to different inertial frames[1]. Even then, the relativistic effects only become obvious if the relative velocities between the frames is high. Much higher than velocities we encounter in daily life. Finally, Special Relativity is limited to idealized situations where acceleration and gravity are absent. Consequently, relativistic phenomena remain abstract and are hard to imagine.

Thought experiments (TEs) are a powerful instrument for physicists to explore new phenomena and expand their understanding of the world. In a TE, physicists can explore the consequences of relevant concepts in an idealized world (Gendler, 2004; Mach, 1896/1976). For example, the consequences of an absolute speed of light and high relative velocities in a world without gravity. A TE happens in three stages. In the first stage, the central question, theoretical basis, and what the idealized world looks like are identified. In the second stage, the TE is performed by making deductive reasoning steps from the initial

[1] An inertial frame is a coordinate system or reference frame that is not accelerating and in which the curvature of spacetime is negligible. This means that the frame is at rest relative to other frames, or in uniform motion and gravity is absent.

scenario to obtain an outcome. Finally, reflection on the entire process leads to the generalized implications of the TE (Reiner & Burko, 2003).

TEs can be a powerful instrument in education as well. When they perform a TE, students reason with a “what if” scenario. This means students must activate and communicate their ideas (Matthews, 1994). In this way, the TE helps students to overcome conceptual barriers and to learn new, abstract concepts (Helm, Gilbert, & Watts, 1985; Velentzas & Halkia, 2013). However, the TE’s educational power is often undermined by its story-like presentation. Let’s take a closer look at two relativistic TEs. This will give us an idea how they are typically presented in textbooks and what reasoning is required to perform them.

> ***Einstein’s train – The relativity of simultaneity:*** *Suppose a very long train that travels along the rails at a constant velocity v. A lamp in the middle of the train is switched on. As soon as the light hits two automatic doors at the front and back of the train, these doors open. The question is whether the events of the opening doors are simultaneous in the reference frame of the train and of the embankment the train is passing by. Suppose a passenger finds themselves under the lamp and passes a traveller on the embankment the instant the lamp is switched on. The passenger on the train will say that light covers equal distances to both doors and that they will open simultaneously. For the traveller on the embankment light will have to travel a longer distance to the front than to the back door. Therefore, this observer will conclude that the doors do not open simultaneously. The overall conclusion of this TE is that events which are simultaneous with reference to the train are not simultaneous with respect to the embankment, and vice versa. (after Landau & Rumer, 1959)*

> ***Light clock on a train – Time dilation:*** *Suppose the same train again, only this time the train is equipped with a light clock. This device measures time by counting the instants a light flash hits the bottom of the train. The light flash is emitted vertically, reflected by a mirror at the ceiling of the train and is returned to the floor of the train again. The question is whether the time interval for one cycle of this process is the same for a passenger on the train and a traveller on the embankment. In the train frame the passenger will observe the light flash travelling vertically up and down. Relative to the traveller on the embankment light will not only travel up and down, but also*

> *in the direction of the moving train. The traveller will therefore conclude that the light flash covers a longer distance. The overall conclusion of this TE is that the light clock in the train will run slower for a traveller on the embankment than for a passenger on the train, and vice versa. (after Landau & Rumer, 1959)*

Both stories first describe an idealized world and pose a central question. After that, the outcome is immediately given. However, the reasoning that leads to the TE's outcome remains implicit. Because of that, students are not stimulated to perform that reasoning themselves.

It can be difficult for students to perform all the required reasoning steps of a TE. They need to reason consistently with an absolute speed of light from each of the two inertial frames. While they are doing that, they also need to assign time and place to events. Many students struggle with the concept of absolute light speed. Even after instruction, undergraduate students can only recite the light postulate, but they do not apply it correctly (Gousopoulos, Kapotis, & Kalkanis, 2016). Instead, students tend to reason with a spontaneous model for light propagation (Villani & Pacca, 1987). The pre-instructional models of secondary students describe light either with a constant speed relative to the light source or to an absolute space (Kamphorst, Vollebregt, Savelsbergh, & van Joolingen, 2019). Furthermore, performing a relativistic TE is a difficult task in itself: Students need to administrate all relative movement of the TE scenario in their minds. As a result, they might not "see the forest for the trees" and fail to grasp the TE's overall conclusion.

A representational tool may support students so they can perform the TE's themselves. This tool should support their explicit reasoning with light propagation. The well-known Minkowsky-diagram seems a likely candidate. However, the abstract nature of this diagram makes it problematic for novice learners to perform TEs in them. We propose that the Event Diagram (ED) is a more suitable tool to elicit student ideas, support consistent reasoning with light propagation, and derive relativistic concepts while performing TEs. Next, we take a closer look at EDs and present some tasks in which TEs are supported with EDs.

2.1. The Event Diagram

EDs graphically represent spacetime and were first proposed by Scherr (2001). An ED shows the position of objects and events at several moments in time, from a specific reference frame. These EDs typically consist of one or two pictures. Scherr employed EDs in tutorials to familiarize undergraduate students with reference frames, spatial measurement and the relativity of simultaneity. The diagram visually organizes the information presented in the assignment, and is occasionally used as an answering format for students to draw the task outcome (see Figure 2.1). However, Scherr's version of the ED does not support representing any intermediate reasoning steps.

We added two features to the ED to make it a tool for student reasoning. First, our EDs consist of a series of snapshots taken at regular time intervals, much like a time lapse movie. Second, the pictures are drawn on a grid. This makes it easy to measure position and distance in the ED (see Figure 2.2). Together, these features make it possible to show the speed of moving objects and draw light propagation in the ED. The outcome of the TE is intentionally not shown in the ED, so students are required to perform the TE themselves. Students perform the TE by drawing light propagation in the ED. For this, the speed of light needs to be given a value that makes sense in the context of the ED. In the tasks of this chapter, light speed was set at three squares per time unit. Through reasoning by drawing, students find out when a specific event occurs (i.e., the doors opening, the light flash hitting the floor of the train) (Ainsworth, Prain, & Tytler, 2011). With teacher supported reflection on the second stage of the TE, students can draw the overall conclusion.

Compared to the traditional presentation of TEs, the ED stimulates students to reason with light propagation more explicitly. Time is represented stepwise in the ED. Therefore, students construct light propagation in a stepwise fashion as well (Kamphorst et al., 2019). To be more specific, students indicate the position of the light flashes in each snapshot. The snapshot in which the light flash and lamp share the same position indicates the time when the light was emitted, and students assign time and place to the event (see also the description of Task 1 and Figure 2.3). Students do not immediately reason about the time between two events, instead they find this as an outcome of the construction process.

Like all external representations, EDs are a simplified and idealized display of reality and are inherently limited. However, our tasks allow students to reflect on these limitations. This reflection enables them to see beyond the representation itself and fathom the relativistic concepts separated from the representation.

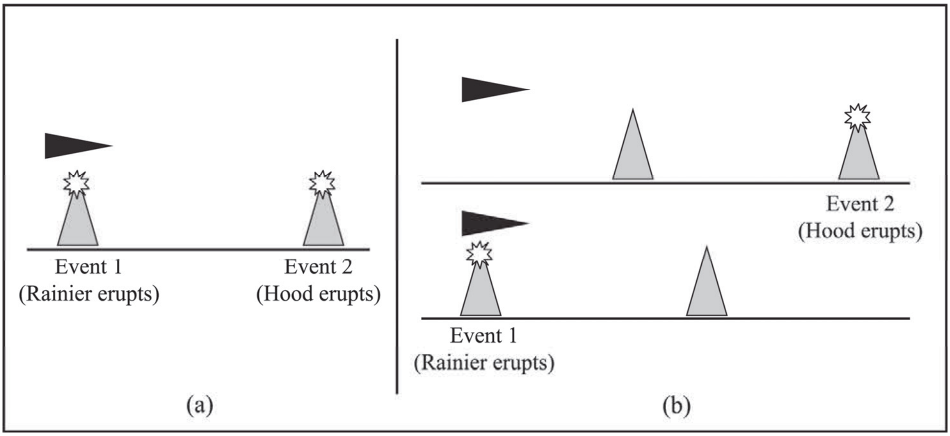

Figure 2.1 Drawn after ED by Scherr (2001, pp.190). This diagram shows the position and time of objects (volcanoes and spacecraft) and events (erupting volcanoes). In the ground frame (a) these events are simultaneous, whereas in the spacecraft frame (b) event 2 happens before event 1

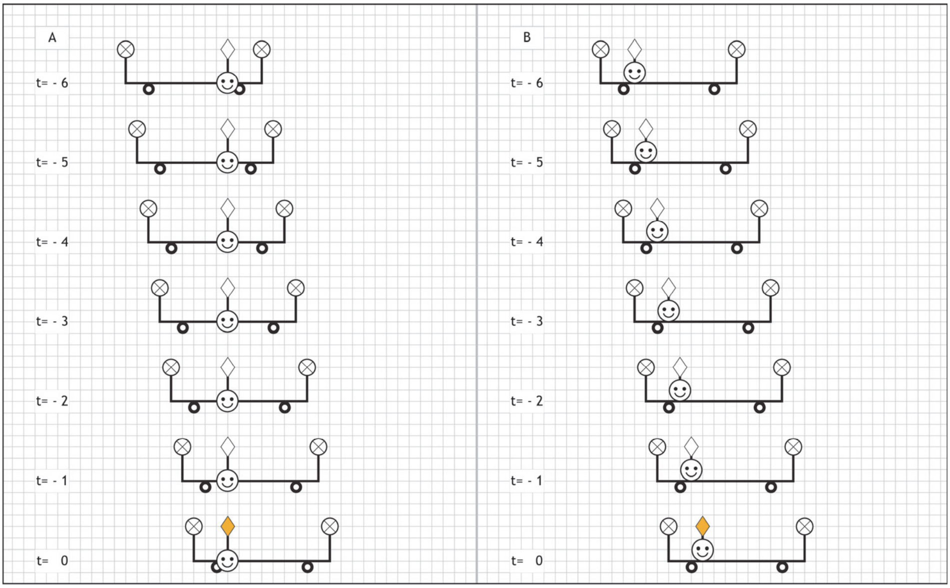

Figure 2.2 EDs supporting a version of Einstein's Train (described in Task 1). Each snapshot shows the position of objects for subsequent moments. Each picture is given a unique time stamp. The observer is represented by the smiley-face, the measuring device by the diamond. To show the key event, two light flashes arriving simultaneously at the measuring device, the diamond is painted yellow. The cart with two lamps (shown by the lamp symbols used in electric circuits) has a speed of one square per time unit, moving to the right.

2.2. Thought experiments supported by Event Diagrams

Each of the following three tasks demonstrates a different feature of the educational power of the TE. The task description follows the three phases of performing a TE:

1. The situation of the TE, central question and supporting ED;
2. The expected student reasoning and task outcome;
3. How students can reach overall conclusion and reflect on limitations of the ED.

Each task is illustrated with a short excerpt of student discourse that shows what kind of student reasoning these tasks can achieve. These data were collected from a study in which the tasks were presented to groups of 2-4 students of 11th grade pre-university secondary education (16-18 years old).[2] The names of the students are fictitious.

2.2.1. Task 1. TE Predicting the past: Eliciting reasoning with light propagation

The aim of this task is to make students aware that light propagation is always measured relative to something. There are different possibilities for this reference frame. The task outcome is influenced by the choice for reference frame in relativistic situations (i.e., relative movement between light source and observer). This TE is a variation of *Einstein's train.* An observer measures the simultaneous arrival of two light flashes at a measuring instrument. These light flashes were emitted by two distant lamps on a cart. The central question is: How long ago were the lamps switched on? To elicit the role of reference frame for light propagation, we developed two versions of this task. Students perform the TE for a situation in which the lamps are moving relative to a stationary observer (Task 1A) and a situation in which the observer is positioned on the cart. In the latter situation, both lamps and observer move relative to the grid (Task 1B). These situations are represented in an ED (see Figure 2.2). The final snapshot $t = 0$ at the bottom of the figure shows the instant the light flashes arrive simultaneously at the observer's measuring instrument. Snapshots above this picture show previous instants where the light flashes were still travelling

[2] Over the course of the research project, we worked with 2 different values of the speed of light in the ED: 2 and 3 squares per time unit. These interviews were conducted with a previous version of the ED in which the speed of light was set at a value of 2 squares per time unit. To prevent confusion, we adapted the numerical value of the speed of light in the quotes of Lisa (Task 1) and Laura (Task 2) to align with the newer version of the tasks presented in this chapter.

towards the researcher. It is up to students to draw the propagation of the light flashes by indicating their position at subsequent moments in the ED. It is not specified in the task relative to *what* the speed of light should be applied. This allows students to explore their own ideas.

Students perform the task by drawing light propagation in the ED. Depending on their pre-instructional model of reasoning, students either draw light propagation with a constant speed relative to the grid or to the lamps (Kamphorst et al., 2019). These two ways of drawing light in the ED are shown in Figure 2.3. Each choice leads to a different task outcome (see Table 2.1).

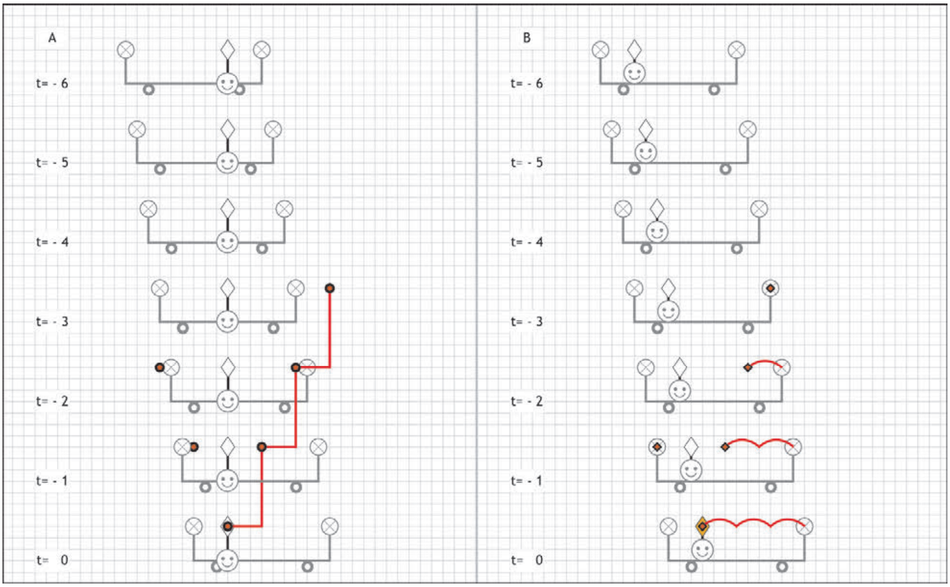

Figure 2.3 EDs supporting Task 1A (on the left) and Task 1B (on the right). The two ways of drawing light are shown with dots and red lines in the ED, each leading to a different task outcome. The left ED shows light propagation drawn relative to the grid. Students construct their drawing by transporting the position of the light flash to the previous picture and count the displacement from that position. The ED on the right shows light propagation drawn relative to the lamp. These students count the distance the light flash has covered relative to the lamp

Table 2.1 Outcome of TE 1 for three light propagation models. The table shows the timestep in which the lamps on the cart switched on. Note that the pre-instructional models lead to the same outcome in both tasks, whereas the light postulate yields different outcomes in Task 1A and 1B

Light propagation model	**Task 1A**	**Task 1B**
Relative to the grid	Left: between t = -1 and t = -2 Right: between t = -2 and t = -3	Left: between t = -1 and t = -2 Right: between t = -2 and t = -3
Relative to the lamp	Left: t = -1 Right: t = -3	Left: t = -1 Right: t = -3
Absolute speed of light (Relative to the observer)	Left: between t = -1 and t = -2 Right: between t = -2 and t = -3	Left: t = -1 Right: t = -3

Comparing the outcomes of different students can be a starting point to address the choice of reference frame as a matter of concern. To this end, the teacher can ask questions that stimulate students to explicate *relative to what* light propagation is constant for *them*. For instance, by asking to explain how they drew light propagation in the ED, or how their drawing method differed from the method of a fellow student. Once students are aware of this role of reference frame, they can also become aware that an absolute speed of light is constant relative to *something else:* The observer. In addition, students are introduced to an important aspect of working with EDs: They should always specify relative to what reference frame they are reasoning with (light)propagation.

Students' reasoning with different pre-instructional models for light propagation

Daniel and Lisa performed Task 1A, each with a different pre-instructional model. Lisa reasoned with a constant speed of light relative to the lamp. Students who reason with this model measure the distance between the lamp and the new position of the light flash.

> ***Lisa**: I thought that he [the light flash] covered nine squares here [t =* 0*, indicating the distance between the measuring device and the*

> *right lamp]. So, in the previous picture [t = -1] he covered three [squares] less, light propagates with three squares per time unit. So, I figured out that he would end up at six [squares, from the lamp].*
>
> ***Teacher**: And before that?*
>
> ***Lisa**: At the third [square from the lamp].*

Daniel performed the task with a constant speed of light relative to the grid. Students with this way of reasoning focus on the position of light on the grid.

> ***Daniel**: The light is emitted from the light point [indicates the position on the grid where the lamps were when the light was emitted]. It does not matter whether the cart is moving. Light is already gone from that place, where it was emitted.*
>
> *[...]*
>
> ***Teacher**: Can you explain the difference between what you did and how Lisa performed the thought experiment?*
>
> ***Daniel**: Yes, she has taken the movement of the cart into account, and I have not.*

Daniel correctly identified that the moving cart caused the difference between the task outcomes he and Lisa obtained. This notion can form a starting point for the teacher to further explore the role of reference frame for light propagation with the students and introduce an absolute speed of light.

2.2.2. Task 2. TE Predicting the past: deriving the relativity of simultaneity

The aim of this task is to derive the relativity of simultaneity as a consequence of the light postulate. This task is based on the same version of Einstein's train as Task 1. Students perform the TE in two different situations. The first situation describes stationary lamps with a moving observer (Task 2C). The light flashes simultaneously arrive at the measuring device when the observer is midway between the two lamps. The second situation (Task 2D) adds a second observer to this scenario. The instant the light flashes strike the measuring device, both observers find themselves in the same position. However, this second observer is not moving relative to the lamps. These tasks are supported by EDs as well (see Figure 2.4). The central question is: When were the lights switched on? A new element in this task is that students perform the TE in two reference frames.

Students are invited to perform the TE by drawing an absolute speed of light in the ED (see Figure 2.4). Nevertheless, students might fall back to their pre-instructional model. The task outcomes for both ways of reasoning are given in Table 2.2. Students who correctly apply the absolute speed of light, find that for the moving observer (Task 2C) the lamps were switched on at two different moments in time, while these events were simultaneous for the stationary observer.

The relativity of simultaneity is the generalized implication of observers assigning different times (and places) to the same event, which in its turn is a consequence of the light postulate. For students to grasp this far-reaching consequence, the teacher could ask how the two observers obtained different outcomes of the TE, which outcomes would be obtained when the roles of the observers were reversed, or what these different outcomes would mean for two events in general. This task confronts students with a limitation of the ED: drawing light propagation in the ED will represent an absolute speed of light for only one of the two observers. This underlines the importance to specify for which observer they perform the TE. Performing this task makes it clear why it is desirable to let the reference frame of the ED and the observer coincide.

Students reflecting on the outcome of the TE

Three students, Jeroen, Kelly and Bart, talked about the task outcome of TE 2. They each had a different interpretation. Jeroen explicated that the outcomes differ from his expectations. This difference made Kelly doubt the light postulate. By contrast, for Bart the light postulate was the reason to accept the counterintuitive outcome of the TE.

> ***Jeroen****: Strange that they [the lamps, seen from the two observers] turn on at different moments, while light [propagation] actually remains the same.*
>
> ***Kelly****: I would wonder if it [light propagation] is really relative to the observer, because here you have two observers and then you get a different outcome [of the TE]. [Points at the light flashes in the ED] …that that [light propagation] is relative to the observer and not relative to the paper or the moment of turning on [of the lamps].*
>
> *[…]*

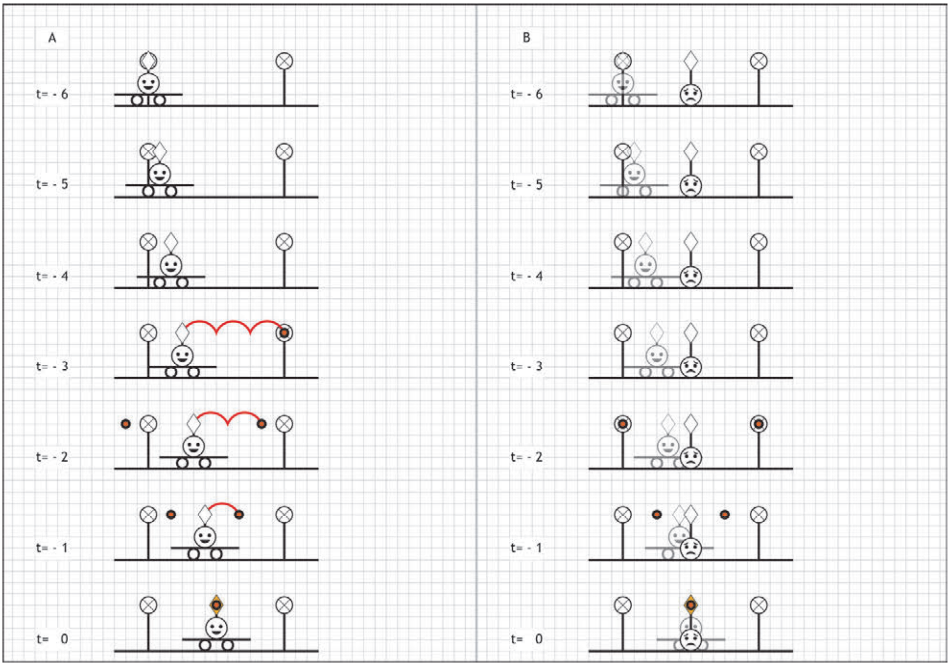

Figure 2.4 The two EDs supporting TE 2. The light flashes drawn in the ED propagate with an absolute speed. Task 2C (on the left) is performed for the observer on the skateboard, Task 2D (on the right) for the stationary observer. In this figure, the observer on the skateboard is given a lighter colour. The red lines show how students construct their drawing, counting the distance the light flash has covered relative to the observer. Students who fall back to their pre-instructional reasoning will obtain the results of Task 2D in both versions of the TE. These students may explain their reasoning the following way: "*They [the light flashes] cover the same distance to arrive in the middle, so they [the lamps] should also have turned on at the same time*" (Daniel)

Table 2.2 Outcome of TE 2 for three light propagation models. The two pre-instructional models will give the same results

Light propagation model	**Task 2C**	**Task 2D**
Absolute speed of light (Relative to the observer)	Left: between t = -1 and t = -2 Right: t = -3	Left: t = -2 Right: t = -2
Pre-instructional model (Relative to the lamp or to the grid)	Left: t = -2 Right: t = -2	Left: t = -2 Right: t = -2

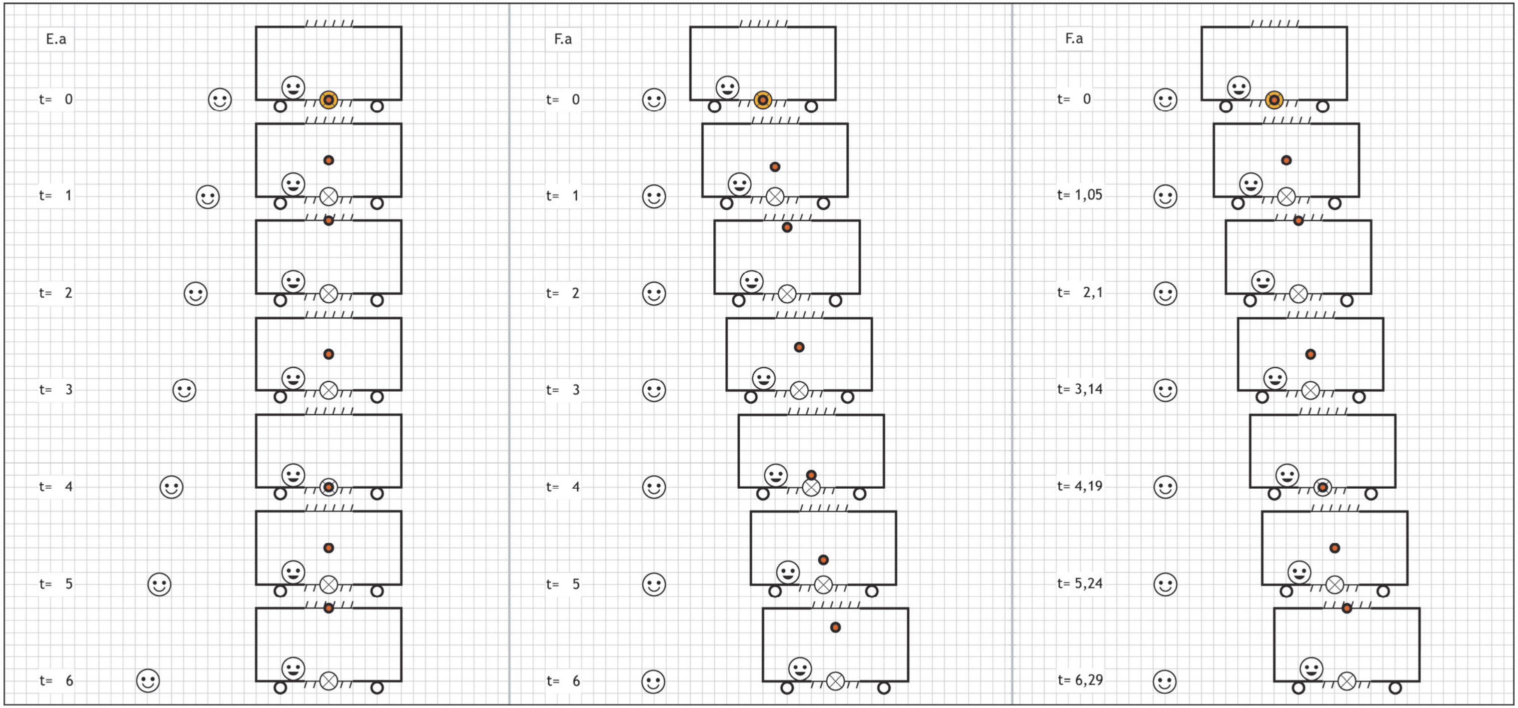

Figure 2.5 three EDs to support the light clock TE. Both observers are shown in the ED, the stationary observer is drawn in black. Task 3E (on the left) shows the situation for the observer with a stationary light clock; Task 3F (in the middle and on the right) shows the same situation from the reference frame of an observers studying a moving system. Light propagation is drawn relative to the stationary observer in the ED. In this ED, the mirrors are shown by the shaded lines, the instant the light flash is emitted by the yellow lamp at $t = 0$, at the top of the figure. The time indications in the student version of Task 3F are left blank, this allows students to deal with drawing light propagation in the TE in two different ways: They either draw light that does not go up exactly three squares per timestep (middle figure), or light that goes up three squares per snapshot and increase the time between snapshots (right figure)

> ***Jeroen**: Because they [the observers] move with different speeds. […] Light moves relative to the observer. So, if the one observer has a speed relative to the other, it [light propagation] will go in a different way. […] It cannot be [a] different [outcome of the task]. Light moves relative to the observer and that is what we did.*

The following fragment illustrates how the students can reflect on multiple observers in the ED. Iris struggled with the two observers in one diagram. In this, she recognized that all observations depend on reference frame. Only, this notion was still counterintuitive to her. Laura explained how this is inherent to the light postulate.

> ***Iris**: But see, they would not understand it [light propagation in the ED], because they both see something different.*
>
> *[…]*
>
> ***Laura**: No, because they both measure those three squares, if they would measure light propagation for themselves.*

Both fragments show that the students explored the consequences of an absolute speed of light and interpret their meaning.

2.2.3. Task 3. TE Light clock: coming to a conceptual understanding of time dilation

This task aims for students to gain a conceptual understanding of time dilation. Through performing this task, students come to understand how time dilation is a consequence of the light postulate. In addition, students understand how the extent of this phenomenon is influenced by the relative speed between the observers. The task follows the scenario of the light clock TE. The central question is: How many timesteps does light need to travel up and down between the mirrors of the light clock? First, students perform the reasoning steps in the train frame (Task 3E). Next, they describe the situation from the frame of the stationary observer on the embankment (Task 3F). Each event diagram shows the situation of the task in the reference frame of the observer that makes an appearance in the thought experiment. (Figure 2.5).

Students draw light travelling up and down between the mirrors (see Figure 2.5). The duration of the time interval can be determined in two ways. Either students count time in the ED, or they divide the travel distance of the light flash by its speed. Students collect the position of the light flash for all timesteps and construct the light path relative to the observer in an ordinary *x,y*-graph (see Figure 2.6). For the observer in the train, light travels up and down vertically. To the observer on the platform light deflects in the direction of movement of the train. This is not clear to all students. These students draw light travelling vertically upward relative to the second observer as well. The ED is designed in such a way that light misses the mirror in that case. It might be helpful to remind these students that all events happen for all observers, although observers may assign different places and moments to them.

One of the difficulties in learning relativity is that it has no daily life reference. To understand why, students need to reflect on the role of relative velocity for the extent to which time dilation occurs. To this end the teacher can ask what would happen to the time interval both observers measure if the relative velocity between the observers would be in the other direction, or if this velocity increases or decreases. If needed, these questions can be supported with their own EDs. The outcome of the TE and these reflections is summarized in Table 2.3.

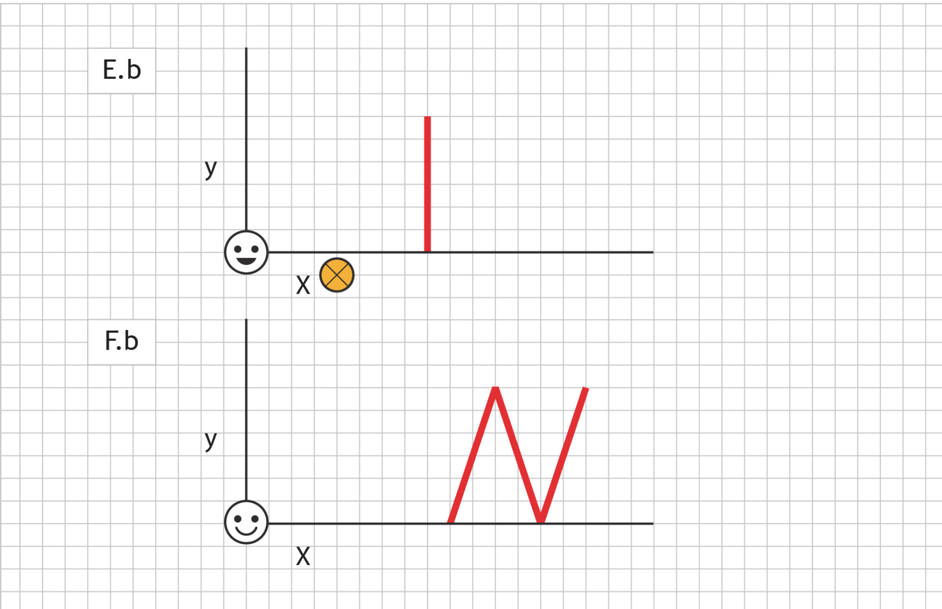

Figure 2.6 The *x,y*-graphs allow students to collect the data of the ED and find the path light travelled relative to the two observers. The lines in the graphs show the light path from t = 0 onward

To come to a more complete understanding of time dilation, this task can be extended. First, the situation can be reversed, performing the TE when the observer on the platform has a light clock. After that, the two situations can be combined, showing that each observer will conclude the clock of the other one is running slow compared to his own. Besides that, the formula for time dilation can be derived from the task outcome. This formalizes the concept of time dilation.

Table 2.3 Outcome of the TE 3: The time interval between light hitting the floor of the train twice from two different reference frames. The answers of how relative velocity influences the extent of time dilation are given as well

Sub question	Task 3E	Task 3F
How many timesteps does it take for the light to travel up and down between the mirrors once?	Δt = 4 timesteps	$\Delta t > 4$ timesteps By using Pythagorean theorem: $\Delta t = 4{,}19$ timesteps Alternatively: Students might use a ruler to measure the distance light travelled
What happens when the cart moves in the other direction?	Δt = 4 timesteps	$\Delta t = 4{,}19$ timesteps
What happens when the velocity increases?	Δt = 4 timesteps	$\Delta t > 4{,}19$ timesteps
And approaches the speed of light?	Δt = 4 timesteps	$\Delta t \to \infty$
What happens when the velocity would decrease?	Δt = 4 timesteps	4 timesteps $< \Delta t < 4{,}19$ timesteps
At what velocity would Δt be the same for both observers?	$v = 0$	$v = 0$

With the formal definition of time dilation, students can reflect on another limitation of the ED. According to this formal definition, the time interval in Task 3F takes on a different value than they have found before ($\Delta t = 4{,}24$ timesteps). Apparently, light covers a bigger distance than one would expect based on the drawing in the ED. This is a starting point to introduce length contraction.

Reflecting on the meaning of the difference in travelled distance

Max and Niels performed the TE of Task 3F. Max initially drew light travelling up in a vertical line. Niels corrected him. The two students then reflected on the task outcome.

> ***Max**: I am not sure if this is correct […] because it goes against my intuition very strongly. That it [the light path] is a straight line, and then again that it is not a straight line.*
>
> *[…]*
>
> ***Niels**: For the other observer [Task 3F] it is […] a zigzag pattern. In that case, [the observer in Task 3F] would think that light goes faster, or that it takes a longer time to go up and down.*
>
> ***Teacher**: Which of the two is it?*
>
> ***Niels**: It takes a longer time, because light has a constant speed.*

Max acknowledged the logic behind how the TE should be performed. However, the task outcome remained counterintuitive to him. When they reflected on the meaning of the task outcome, Niels first reconsidered if he should use the light postulate to interpret the results. He came to a decision and showed the relation between the outcome of the TE and the light postulate.

2.3. Conclusion and Outlook

To wrap up, we have shown how our tasks stimulated students to perform TEs by drawing light propagation in EDs. To achieve this, we have added extra snapshots to the diagram and drew it on a grid. Because we only present the setup and central question of the TE, students' reasoning is supported even further. The examples of student reasoning illustrate that this is a promising approach to bring the educational power of TEs to secondary students. These examples demonstrate that the tasks allow students to explore their ideas on light propagation and become aware of the importance of reference frames for light propagation. Furthermore, students derived relativistic concepts and explained how they are related to the light postulate. Not only can EDs productively support student reasoning, we have also shown how students can reflect on the limitations of the ED. In educational practice, these limitations can be used productively to introduce new aspects of relativistic reasoning and new relativistic concepts. In addition, we expect EDs can be used as a steppingstone to introduce the more formal Minkowsky-diagram.

Chapter 3

Students' Pre-instructional Reasoning with the Speed of Light in Relativistic Situations

Kamphorst, F., Vollebregt, M. J., Savelsbergh, E. R., & van Joolingen, W. R. (2019). Students' pre-instructional reasoning with the speed of light in relativistic situation *Physical Review Physics Education Research*, *15*(2), 020123.

Abstract – Special Relativity Theory (SRT) has recently gained popularity as a first introduction to “modern” physics thinking in upper level secondary physics education. A central idea in SRT is the absolute speed of light, with light propagating with uniform speed relative to the reference frame of the observer. Previous research suggests that students, building on their prior understandings of light propagation and relative motion, develop misunderstandings of this idea. The available research provides little detail on the reasoning processes underlying these misunderstandings. We therefore studied 15 11th grade secondary education students’ pre-instructional reasoning about the speed of light in a qualitative study, probing students’ reasoning through both verbal reasoning and drawing. Event Diagrams (EDs) were used as a representational tool to support student reasoning. Results show that the students productively use EDs to reason with light propagation. In line with previous research, we found two alternative reference frames the students could use for uniform light propagation. Most students in our sample evaluate light propagation in several reference frames, showing flexibility in their use of reference frames. Some of these students experienced a conflict between an alternative reference frame and the speed of light. These students changed their reasoning; this change has promising features for designing education.

Keywords – Special Relativity Theory; secondary education; reasoning; interviews; interpretative analysis

3.1. Introduction

Internationally, the interest for introducing modern physics in secondary school is growing. Novel teaching approaches about topics such as quantum mechanics, nano-science and Einstein's theories of relativity, both Special and General, have been developed and included in national curricula (Dimitriadi & Halkia, 2012; Henriksen, Bungum, Angell, Tellefsen, Frågåt, & Bøe, 2014; Kersting, Henriksen, Bøe, & Angell, 2018; Laherto, 2011). This is also the case for the Netherlands, where the modern topics Quantum Mechanics, Particle Physics and Special Relativity Theory were introduced in the upper years of pre-university level secondary physics education.

These modern physics topics are characterized by their mathematical complexity, their lack of daily life reference, and their often counter-intuitive concepts and consequences. Students have not yet mastered the formal techniques to solve meaningful quantitative problems. This favours a conceptual approach in secondary schools. To gain a conceptual understanding, students need to adopt highly formal and radically new frameworks. At the same time, students cannot resort to life world experiences. Therefore, in modern physics, conceptual learning might prove to be even more difficult than it is for classical physics topics, where students do have direct life world experience with the phenomena at hand (see, e.g., Limón, 2001)

A fundamental premise in conceptual learning is that new conceptual knowledge builds on previous mental structures (concepts, experiences; see, e.g., Disessa, 1996; Shtulman & Valcarcel, 2012). Therefore, the introduction of new concepts needs to be closely connected to students' prior thinking (Klaassen, 1995; Strike & Posner, 1992). It is thus essential to acquire a detailed image of students' ideas and prior thinking related to principles and concepts of these modern physics topics as well. A continued interest in studies with the focus on students' difficulties or misconceptions and students' mental models illustrates this need (c.f. Krijtenburg-Lewerissa, Pol, Brinkman, & Van Joolingen, 2017; Savall-Alemany, Domènech-Blanco, Guisasola, & Martínez-Torregrosa, 2016). With this study we aim to contribute to these efforts for the topic of Special Relativity Theory (SRT).

A main reason to include a modern subject such as SRT in secondary education is that it is fundamental to modern physics, and an excellent example of a major paradigm shift in the thinking of physicists. From thinking in terms of an absolute space and time, physics moved towards thinking in a combined spacetime with an absolute speed of light, the properties of which depend on the relative motion of observer and observed phenomena. Basic concepts such as simultaneity, space and time required new definitions.

SRT is a theory of counterintuitive concepts and consequences. The theory is based on two postulates. The relativity principle states that all laws of nature are the same for observers moving at a constant speed relative to each other. The light postulate states that: *"Light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body"* (Einstein, 1905/1952a, p.37). Combined with the relativity principle, this postulate implies that if two observers are in relative motion to each other, and both look at the same travelling light phenomenon, each will see the light travel at the same speed *c*, each relative to their own point of view. This speed is referred to as the *absolute* speed of light.[1] The concept of absolute speed by itself may seem counterintuitive, but its implications might be even more counterintuitive from a classical point of view: Two observers moving relative to each other will observe different values for the distance the light has travelled and for the time that passed by between two events. This means for instance, that a clock moving at a certain speed will run slower than one at rest relative to the observer and the length of the moving clock in the direction of movement will be smaller than the length of a clock at rest relative to the observer.

SRT is difficult to learn for students. The consequences of SRT do only become apparent at high speeds. Therefore, we do not have any daily life references for relativistic phenomena. When SRT was first introduced, physicists struggled with the shift towards a combined spacetime, and it should not be surprising that today's students also struggle with the basic relativistic concepts after their first SRT courses (Aslanides & Savage, 2013; Pietrocola & Zylbersztajn, 1999; Scherr, Shaffer, & Vokos, 2001). The struggle with relativistic concepts might be rooted in problems with the postulates, since all relativistic concepts are derived from them. Several studies have addressed the relativity principle in both classical and relativistic physics (Panse, Ramadas, & Kumar, 1994; Pietrocola & Zylbersztajn, 1999). However, students' understanding of the light postulate is less well documented, especially at the secondary education level. We expect that these students will also struggle to understand the light

[1] According to SRT, the speed of light is absolute. This means it is constant (does not vary over time), it is uniform (equal in all directions, and at all points in space), and it has the same value relative to any observer, regardless of whether the observer is stationary or moving relative to the light source.

postulate in view of their prior understandings of light propagation, and that it might be helpful for teaching to gain more insight into their prior understanding.

Young children often have an idea of light as either associated with its source or effect. From the age of 13 or 14, children more often recognize light *"as a distinct entity, located in space between its source and the effect it produces"* (Guesne, 1989, p.11). Once children come to see light as a distinct entity in space, they still consider light propagation and light travel time only in the context of very long distances, for instance the distance between the Earth and the Sun. In the context of their own environment, light arrives instantaneously (Guesne, 1989). Since SRT is taught in the final years of upper level secondary education, we expect these students to be able to reason with light as an "entity in space." However, relativistic reasoning requires students not only to reason with light as an entity in space, but also to apply a notion of propagation time of light even in contexts with small distances, thereby acknowledging that light has a finite speed.[2]

At the upper end of the educational spectrum, Villani and Pacca (1987) studied physics graduate students' ideas about the speed of light after they had completed courses on SRT. Most students, even at this advanced level, were committed to the idea that relativistic effects are only apparent. They thought that there is only one true value for the speed of light, and that this true value is measured relative to the light source, independent of the observers' reference frame. If even these graduate students do not reason along the lines of the light postulate, we cannot expect that introducing the light postulate by offering a definition, an approach also adopted in many secondary school books, will lead secondary education students to reason along the lines of the light postulate.

Secondary education students' ideas about light propagation in relativistic contexts prior to instruction are not well documented. However, the study by Dimitriadi and Halkia (2012) of secondary education students' use of the light postulate in thought experiments *after instruction* gives some insight into student talk about light propagation. In this study, some of the student's statements sounded similar to the light postulate, while at the same time suggesting variable speeds relative to the observer. We can illustrate this with a student quote: *"Light always has the same speed. What the observers measure… well, this depends on how fast they are going."* (Dimitriadi & Halkia, 2012, p.2577). From a physicist's perspective the student quote seems inconsistent:

[2] As opposed to an infinite speed of light, which will result in an instantaneous arrival of light .

The student first acknowledges the light postulate and then denies it in the same sentence. But if we assume that the learner tries to maintain a coherent worldview (Klaassen & Lijnse, 1996) the student statement is consistent with the idea that light has a constant speed relative to an absolute space to which all observers agree. In fact, Dimitriadi and Halkia also conclude that students prefer to describe motion relative to the Earth, which can also be seen as a kind of absolute space. This dissonance between physics theory and student ideas is also mentioned in the research of Hewson, who found that at first glance university students accept relativistic concepts, such as the light postulate, but that further inquiry reveals they do not understand them in the intended way (Hewson, 1982).

In the studies of Dimitriadi and Halkia (2012) and Villani and Pacca (1987), the underlying reasoning processes remained mostly invisible, which makes full interpretation of students' statements hard. For instance, the student quote in the previous paragraph shows that statements about a constant speed of light cannot be interpreted without knowing the reference frame relative to which this constancy holds for the student. Thus, when assessing student ideas on light propagation, this needs to be done in a fashion that makes the reference frame in which students do reason explicit. As light propagation always involves space and time, drawings might be a helpful means to have students make the temporal and spatial aspects of their reasoning explicit (Ainsworth, Prain, & Tytler, 2011). Therefore, using drawings in addition to verbal reasoning seems a promising approach to discover the subtle differences between students' and physicists' reasoning and to bring ideas to light that might prove to be helpful in the teaching and learning of the light postulate.

In the literature, we identified the Event Diagram (ED) as a suitable instrument to make the reasoning process visible and to elicit students' implicit usage of a reference frame (Scherr, 2001). An ED represents something happening as a series of snapshot pictures, showing the positions of objects at subsequent moments in time. The ED thus represents a series of events in spacetime as seen from a specific reference frame, and different EDs can be used to present the same series of events from different frames of reference. We expect that in addition to being a powerful tool for teaching (Scherr, Shaffer, & Vokos, 2002), EDs can also be a tool for eliciting student reasoning if students are to construct light propagation by drawing in these diagrams by themselves.

Like in a time lapse movie, time in the ED has a discrete character. Students need to reason stepwise to reach their conclusion. This approach differs markedly for the more usual representations, where only the end or the beginning of the series of events will be mentioned explicitly. Thus, by introducing EDs, it might be expected that the reasoning task alters in a qualitative way. Therefore, we are also interested in the contribution that EDs make to student reasoning, their potential as an evaluative tool as well as a didactic resource.

To summarize, the literature shows that students' interpretations of the light postulate can be problematic indeed. Rather than using an absolute speed relative to the observers, students were found to reason with a uniform speed of light relative to absolute space (Dimitriadi & Halkia, 2012), or relative to the light source (Villani & Pacca, 1987). Although this is a valuable starting point, both studies describe student answers without the underlying reasoning and focussed on post instruction reasoning. In order to teach the light postulate more effectively, we need a more detailed understanding of how secondary education students construct light propagation and uniform speed of light prior to instruction. This qualitative study aims to elicit students' reasoning in a step-by-step fashion, using EDs, to identify elements in their reasoning that might inform our design of SRT education. We therefore ask the following research question:

> *Using Event Diagrams, in what ways do secondary education students reason with light propagation in relativistic situations prior to instruction?*

3.2. Method

To answer our research question, we conducted a clinical interview study, following the approach described by Ginsburg (1981). In this approach, the researcher presents a task to the participant, and invites the participant to reflect on the task. The researcher then asks further questions contingent on the participants' responses. This process allows verbalization on the student's part, exposing underlying cognitive processes. The flexible nature of the clinical interview allows the researcher to probe student reasoning until the participant has given a complete answer.

3.2.1. Participants

The 16 participants were 11th grade students of pre-university secondary education in the age range of 15 to 18 years, from two different schools. The researcher or their physics teacher approached participants in class with an open invitation. Initially more boys volunteered, after which girls were invited more explicitly a second time. Because of a failed audio recording, the final analysis included data from 15 participants (ten boys and five girls).

The participants in this study were all enrolled in the science track. Both schools taught SRT as part of physics education, but the participants had not received any education on this topic prior to the study. Electromagnetic radiation and the wave-particle behaviour of light had been discussed earlier in the school year.

3.2.2. Procedure and materials

The interview consists of three phases: An introduction, a non-relativistic task (A) and a relativistic task (B), each consisting of three subtasks. The participant is asked to think aloud, to express their reasoning in the ED, and to explain what will happen based on their drawings. This way, we use three perspectives: Doing, describing and explaining, to probe student reasoning. If the coherence between these three perspectives is not apparent to the researcher, the participant is asked to elaborate. We also expect participants to show consistent reasoning throughout all subtasks. At the end of each phase, the researcher summarizes the main insights that have been addressed in order to ensure each participant has the required information at the start of the next task.

Introduction phase

The aim of the introduction phase is to check whether the participant understands the basics of seeing objects and the speed of light. The researcher presents a concept map (Figure 3.1), and the participant is asked to talk about light. Subsequently, the researcher asks for examples of situations in which one would notice that light has a speed, and to explain why one can see a pencil that is lying on the table.

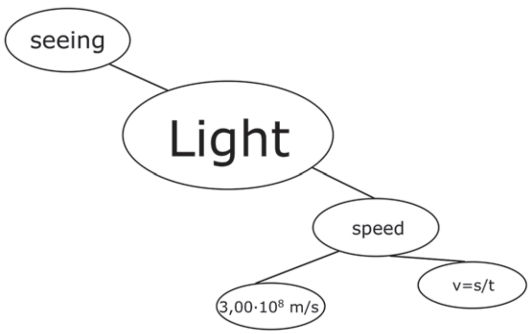

Figure 3.1 The light concept map to support students to talk about the basics of seeing and the speed of light

Reasoning Tasks A and B

Reasoning Task A and B consist of three subtasks each. All (sub)tasks are about physically the same situation: A light flash is emitted by a lamp in a room. At each side of the room, there is a door connected to a light sensor. When the light strikes a light sensor, the door at that side of the room will open. In Task A, the observer has a fixed position relative to the room with each subtask having the observer in a different position. In the subtasks for Task B, the observer and/or the room are moving, relative to each other or relative to the paper.

The reasoning tasks are presented verbally and illustrated with EDs. At the start of the interview, the researcher briefly explains the way time and motion are represented in EDs, that light has a speed of two squares per time unit in these diagrams, and how to draw light in the EDs. After this instruction phase the participant is free to choose a drawing method that suits them best.

At the start of each subtask, the researcher describes the situation and asks the participant to take the place of the observer. Each time the participant is asked the following:

1. At what time do the doors open after the light flashes?
2. When will the observer see this happen?
3. Do the doors open simultaneously?
4. Does the observer see the doors open simultaneously?

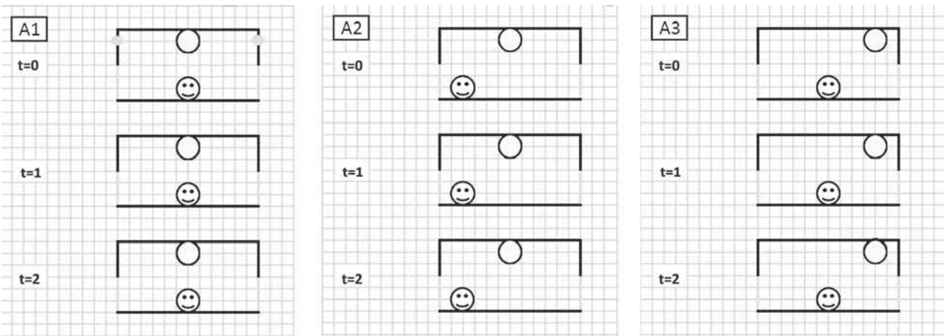

Figure 3.2 Task A. EDs to probe reasoning with signal travel time and correction for signal travel time. In the diagrams, the room is depicted as a rectangle, the light source is the circle at the top, the doors are the lines at the side of the rectangle and the observer is represented by the smiley face. To prevent an overcrowded ED, the sensors, the dots above the doors, are only shown in the first picture of Task A1. Participants are instructed that the sensors are present in all the tasks

If a participant has trouble coming up with an answer, the researcher stimulates the student to use the ED in constructing their answer. Once the participant has completed all three subtasks of Task A or B, they are asked to compare the task outcomes. The researcher asks participants to compare their answers of the different subtasks and explain why the EDs lead to different or identical answers. The participants are also asked to compare subtask B3 to subtask A1, since from a relativistic perspective these tasks are the same.

The EDs used in this study present the passing of time using sequences of 6-12 pictures representing the layout of the situation at subsequent moments in time. The first instant is shown at the top of the page, the last at the bottom. Each picture is drawn on graph paper and shows the position of the lamp, the room and the observer. The propagation of the light is not shown in the pictures: It has to be constructed by the participant themselves. Figures 3.2 and 3.3 present the first pictures for the subtasks of Task A and B, respectively.

The aim of Task A is to probe whether participants reason with a constant speed of light in the ED, and whether they consider signal travel time. In subtask A1, both the lamp and the observer are in the middle of the room. This means that light will reach the sensors at both ends of the room simultaneously and that the observer will see the doors open simultaneously as well. In the ED, applying a two squares per time unit speed of light, the doors will open at $t = 3$, and the observer will see this happen at $t = 6$. In subtask A2 the lamp is still in the middle of the room, which means that light reaches the sensors simultaneously at $t = 3$. However, the observer is positioned closer to the left-hand door, which means that they see the left-hand door open first at $t = 4$ and the right-hand door open at $t = 8$. In subtask A3, the lamp is positioned closer to the right-hand door. As a result, the doors will not open simultaneously. The right-hand door opens at $t = 1$ and the left-hand door at $t = 5$. The observer is still in the middle of the room and sees the doors open at $t = 4$ and $t = 8$, respectively. We expect that participants who reason with a constant speed of light will draw light that covers equal distances for each time interval in the ED. Participants who consider signal travel time, will say that the observer sees the doors open a while after the event has happened. On the other hand, participants who do not reason with a finite speed of light will say that the doors open instantaneously.

Task B is designed to clarify how students conceptualize the constant speed of light in situations where the lamp has a relative speed to the observer. In subtask B1, the room is moving relative to the graph paper and the observer.

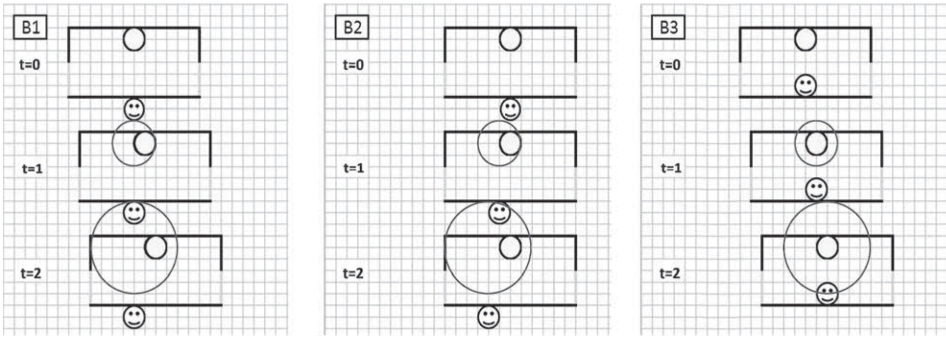

Figure 3.3 Task B. EDs to probe the reference frame in which participants think light propagation is uniform. The grey circle represents the correct answers according to SRT. These were not included in the version given to the students

When students reason with a constant speed of light relative to the observer, they will conclude that light reaches the sensor for the left-hand door first at $t = 2$ and that the observer will see this at $t = 4$. The right-hand door will open at $t = 6$ and the observer sees this at $t = 12$. The student will conclude that the doors do not open simultaneously, and that the observer will not see this happen simultaneously either. However, if a student reasons with a constant speed of light relative to the light source, they will conclude that both doors open simultaneously at $t = 3$. In subtask B2, the observer is moving relative to the graph paper and the room. Students who apply the light postulate will obtain the same task outcome as in subtask B1. However, if students do not apply the light postulate and reason with a constant speed of light relative to the lamp or the graph paper instead, they will conclude that both doors open simultaneously at $t = 3$. Subtasks B1 and B2 will give an initial idea of whether a student reasons with an absolute speed of light or an alternative reference frame. Subtask B3 will give more clarity of which alternative reference frame this might be. In this subtask both room and observer move relative to the graph paper. Students who reason with a constant speed of light relative to the lamp will obtain the same answers as in subtask A1, whereas students who reason with a constant lightspeed relative to the graph paper will obtain similar answers as in subtask B1.

3.2.3. Data collection

Participants were interviewed individually for 45-60 minutes. We video-taped the interviews and we collected the Event Diagrams participants produced. Interviews were transcribed verbatim. Comments for clarification are placed within square brackets.

3.2.4. Analysis and quality assurance

To obtain a full account of student reasoning, we used an iterative approach in which all data sources (video, transcript, EDs) were analyzed together. We followed the method of interpretative analysis described by Clement:

> *Essentially, the scientist aims to construct or piece together a theoretical model in the form of a conjectured story or a picture of a hidden structure or process that explains why the phenomenon occurred. […] the initial model is evaluated and revised in response to criticisms. […] In this method, analysts construct, criticize, and revise hypothesized models of mental structures and processes repeatedly while using them to explain as much of the data in a protocol or a set of protocols as possible. (Clement, 2000, p. 544)*

Our analysis is composed of two phases. In the first phase we familiarized ourselves with the data. For part of the data (7 students), characteristic student quotes and task outcomes that were indicative of the use of a particular reference frame were coded in an open fashion. For example, the student quote "*so here at t is zero, [the light] is still in the lamp itself. At time one [the light] is two squares further … At time three it is again two further […] So eventually [..] in this room [B1], the light arrives at both sensors at the same time and so you see that both doors, they open at the same time.*" (Nick) was coded with "doors open simultaneously, B1." The drawing showed that Nick counted the two squares relative to the lamp. Therefore, the drawing, together with the quote, was also coded with "relative to lamp." These coded segments of all tasks together formed the input to interpret student reasoning. If a student would consistently apply the same reference frame over all subtasks, this person could be classified as holding that particular view on uniform light propagation.

We created a holistic narrative of each participant interview. This was a chronological description of the interview, which focused on what participants said and drew about light, the speed of light, light propagation, and task outcome. The narratives illustrate how participants explain that reasoning pattern (interpretative analysis, Clement, 2000).

The second phase covers the entire data set. The data was coded and interpreted as described above. In the end we grouped the students with similar reasoning patterns and looked for similarities within these groups and differences between the reasoning patterns (thematic analysis, Braun & Clarke, 2006). If participants did not fit one of the categories at first glance, they were discussed in the research team until consensus about their reasoning was reached.

3.3. Results

In this section we will first discuss whether the aims of the tasks were met. Subsequently we will discuss the alternative reference frames the students use when they reason with light propagation in relativistic tasks, and the results of Task B will be discussed more in depth.

3.3.1. Introduction phase

The aim of the introduction phase was to check whether participants understood the basics of seeing objects and speed of light. All participants mentioned that the speed of light is constant.

Non-relativistic Task A aimed to familiarize students with the reasoning task and the EDs. Participants did not express difficulty with the reasoning task itself. The nonrelativistic task could easily be solved by measuring the distance light had to cover in the ED and then applying basic reasoning with longer distances taking longer time for light to cover.

Before the researcher instructed participants how to draw light propagation in the ED, participants used the EDs in three different ways. Participants either only drew the light emitted in the first picture ($t = 0$) (Figure 3.4, left-hand ED, (7/15)), or tried to fit all events in one picture (Figure 3.4, middle ED, (4/15)). These participants did not use the time dimension of the ED, even though they had a chronology of the events in explaining their drawing. A few participants (3/15) did use the discrete time dimension of EDs spontaneously. They drew the events spread out over three separate pictures (Figure 3.4, right-hand ED). One participant did not draw in the ED.

After instruction on how to use EDs, all participants could draw light propagation by using the time dimension of the EDs. All participants drew light that propagated with a constant speed in Task A. An example is shown in Figure 3.5. The dot and circle in the first two pictures were drawn by the researcher; the other circles were drawn by the participant. After instruction, participants were free to choose their own way of drawing light in the ED. We could not find any relation between drawing method (wave fronts, horizontal lines, dots) and reference frame for a uniform speed of light.

The aim of Task B was to find out if students used an alternative reference frame for light propagation. To solve Task B students had to use the ED.

Fourteen out of the 15 students could work with the ED in the intended way, constructing their answer step by step and using the time dimension of the ED to their advantage. One student kept measuring distances and ignored the time dimension of the ED. Although she received explicit instruction how to use the diagram, she did not work with it in these relativistic tasks. We therefore could not use her answers to assign a reference frame for uniform light propagation.

Two participants had unproductive associations with their drawn wave fronts in the ED. The images triggered thoughts of the Doppler shift, blue shift and red shift from starlight and water waves in front of a boat. These associations made the task more difficult for the students, but they still managed, so their interviews were included in our analysis of Task B.

All participants adopted stepwise reasoning approaches, as illustrated by this quote from Kevin:

> ***Kevin****: It [the light] will be emitted here…. Then it will … let me think … but yes, I think just two squares further … so here… there.*

At each step, participants would determine the distance the light had moved since the last time unit, thus determining the position of the wave front for each time unit in the ED. In this, a combination of reasoning with distance and determining the position of the light flash in the ED was used.

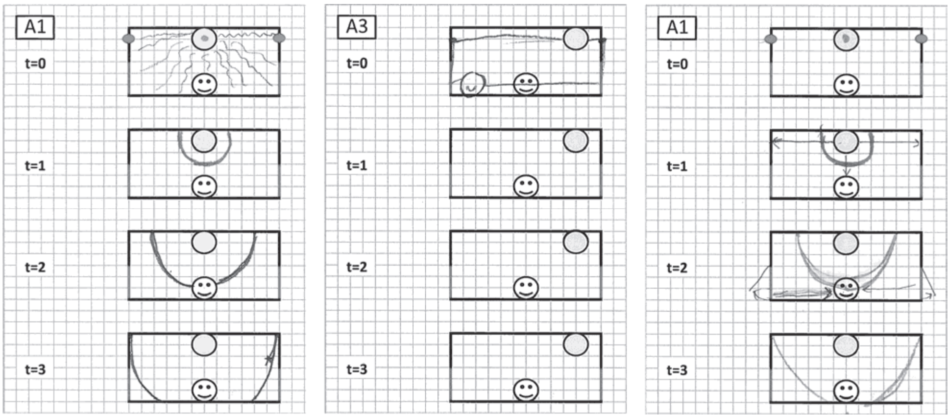

Figure 3.4 Participants used EDs in several ways. Light going in all directions (left-hand ED), indication of the path light covers (middle ED) and individual time units for different events (right-hand ED). The semicircles represent wave fronts. How to draw wave fronts is part of the instruction on working with EDs in subtask A1

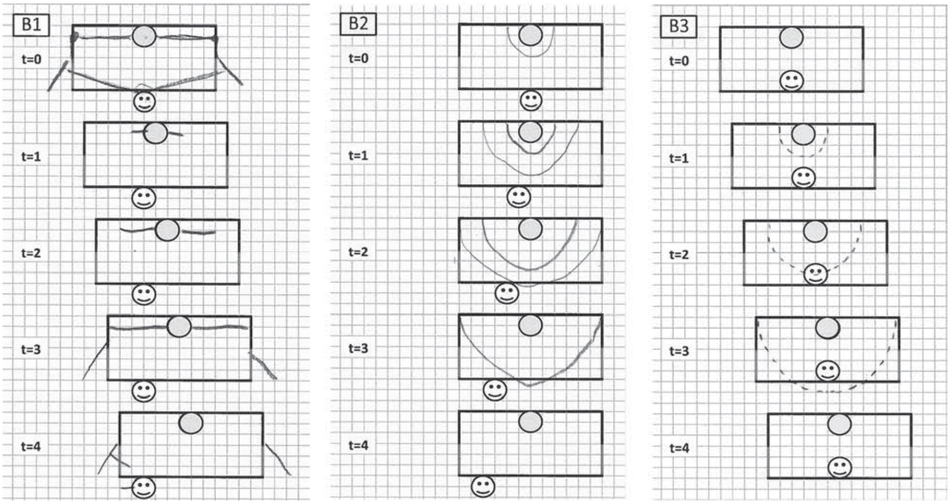

Figure 3.5 EDs of participants who drew uniform light propagation relative to the lamp. The position of the light flash changes with two squares relative to the position of the lamp. The ED on the left shows the drawing of a participant who indicated the distance the light has covered as a path length. The other participants drew wave fronts

3.3.2. Alternative reference frames for uniform speed of light

As discussed above, 14 participants could work with the relativistic Task B. In the following section we will discuss the line of reasoning of these 14 students more in depth.

All 14 participants took a similar approach to Task B: They drew wave fronts and determined the position of the light flash in the ED. However, there is an important difference in their answers. This difference lies in the "reference frame" they used to determine the distance the light has moved relative to its position in the previous picture. For one group of participants, light seemed to propagate with a uniform speed relative to the lamp in all three situations (Figure 3.5). For another group, the wave fronts seemed to have their origin point on a fixed point on the paper (Figure 3.6). Both groups of participants showed there was one reference frame in which the speed of light was uniform for all three situations. They only differed in which reference frame this should be: The reference frame of the lamp, or the reference frame of the graph paper. These reference frames did not coincide with the observer in all situations. So, although participants were asked to reason from the perspective of the observer, they drew uniform light propagation in a different reference frame. We will refer to this as "reasoning in the frame of the lamp (or graph paper)."

Some participants started out with reasoning in the reference frame of the lamp, and switched to the reference frame of the graph paper while they performed the task. Furthermore, one participant showed characteristics of both frames in his reasoning.

Finally, one participant could not be placed in this dichotomy: She drew a uniform speed of light relative to the observer. This participant explained her reasoning referring to relativity theory and the light postulate. As it turned out during the interview, this participant had extensively studied Special Relativity as a personal side project. Therefore, her reasoning is not representative of reasoning teachers could expect in their classrooms. However, this participant showed that the task design is also suited for reasoning along the lines of SRT. An overview of the different reference frames and participants is given in Table 3.1. Not only did these groups think differently about light propagation, they also had a different interpretation of how movement in the task should be described.

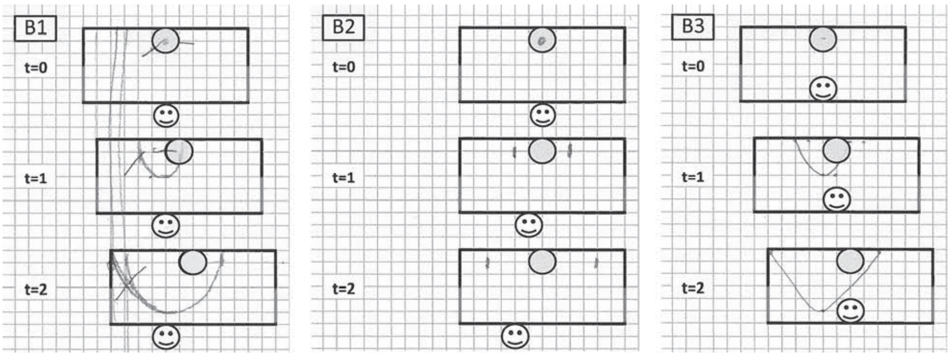

Figure 3.6 EDs of participants that drew uniform light propagation relative to the graph paper. The position of the light flash changes each timestep with two squares relative to the position on the paper the light flash had in the previous time unit. The ED in the middle shows that the participant only indicated the position of the wave front in the horizontal direction. The other participants drew wave fronts

Table 3.1 Number of participants per reference frame for uniform light propagation

Reference frame	Number of participants
Observer	1
Lamp	4
Graph paper	4
Change: lamp → graph paper	4
Combination: lamp & graph paper	1

Reference frame lamp and room

Participants who drew light with a uniform speed relative to the lamp said the doors open simultaneously in all situations. The following quotes illustrate typical arguments, solely based on the geometry of the situation:

> ***Tim****: For the doors open at the same time in B1, as well as B2 [and] B3, because the lamp is, I think, just in the middle of the room.*
>
> ***Anouk****: Actually, ehm, in each situation here [B1, 2 and 3], exactly the same thing will happen. So, the light will turn on, and ehm the doors open at exactly the same moment because [the lamp] is exactly in the middle [of the room]. […] So ehm the light will just ehm move forward with a certain speed. Even if the observer or the box is moving.*

For the students taking this approach, all that mattered are relative positions. The relative movement of the room and observer did not influence light propagation for the students with this mode of reasoning.

In principle, the observed reasoning patterns can be explained from participants' reasoning with a constant speed of light relative to the lamp or to the room. In our task design, the lamp and room were always stationary relative to each other, so we cannot make a clear distinction between these reference frames for uniform light propagation, and we will call this reference frame the lamp-room frame from now on.

Reference frame graph paper

Participants who drew light with a uniform speed relative to the graph paper said that the doors would open simultaneously in subtask B2, but in subtasks B1 and B3 the left-hand door would open first.

Participants were focused on what is moving in the situations when they oriented themselves on the tasks:

> ***Kevin****: Does the room move here, or the person?*
>
> ***Niels****: […] but does the room, does it move to the right, or does the observer move to the left?*

When asked whether this would matter, the participant answered affirmative. Participants concluded that the room moves in situations B1 and B3, and the observer moves in B2: all this movement is described relative to the graph paper.

When explaining the outcomes for subtasks B1 and B3, participants would focus on movement of light and objects in the ED again:

> ***Thomas****: The light is emitted from the lamp and before it reaches the sensors, the distance decreases. So, the required time [for the light to reach the sensors] decreases.*
>
> ***Kevin****: Well, ehm, because […] the room moves, the light will ehm, move in the same way, but the room with the lamp will move further to the right. So it will, at some moment it will ehm … it seems as if the light is more to the left of the lamp than it actually is.*

According to Thomas, light had a shorter distance to cover because the room was also moving (relative to the graph paper). Kevin used the same line of reasoning, but also expressed that light had covered a bigger distance relative to the lamp than what one would expect in a non-relativistic situation. Kevin did not express anything that would suggest that he thinks this bigger distance contradicts with a constant speed of light.

To these participants subtask B2, where the room is at rest relative to the paper and the observer is moving, is rather different from B1. Even though the relative movement between the lamp and the observer is the same:

> ***Kevin****: In this situation, the doors will open simultaneously, […] The light will reach the sensors simultaneously because it [the room] is standing still and not moving.*
>
> ***Thomas****: With B1 […] the room moves, with B2 the person moves. That is why with B1 ehm, the doors do not open simultaneously, and with B2, ehm, because the room is standing still, the doors do open simultaneously.*

Change of reference frame

Four participants initially answered and drew light propagation in line with reasoning in the reference frame of the lamp-room frame. During the interview, they changed their answers, clearly stating the previous answers were wrong. They proceeded with the task by drawing uniform light propagation in the reference frame of the graph paper. We will refer to this process as "changing reference frame." This process can prove to be informative for designing education in which students need to change their reasoning from using an alternative frame to the frame of the observer for light propagation.

Two participants changed light propagation frame because they became aware of a different option and found this option more plausible. We will illustrate this with the case of Nick. Initially Nick reasoned with light propagation in the lamp frame in subtask B1:

> ***Nick**: To the observer it feels like, the light seems to have gone slower, since […] the entire room, with the lamp in it, moves away from the observer.*

This changed later in the interview, when Nick looked again at subtask B1.

> ***Nick**: But…actually, the light has already been emitted, so it just still covers the same […] distance. […] This means that we, according to us, the lamp is still above us […], but the room has moved one square to the right. […] Because technically, relative to this door [points at the right door], he [the light] moves only one square per second to the right.*

This reasoning was consistent with a uniform speed of light relative to the graph paper. Nick explained that light still covered the same distance per time unit when the room moves relative to the observer. In both his answers, Nick mentioned that the speed of light is different when seen from another reference frame. Eventually, that light was emitted at $t = 0$ and that the lamp moved away from that point on the graph paper, seemed to be the reason that Nick switched to a different reference frame for light propagation. In his answer Nick reasoned also in the reference frame of the observer (*"according to us, the lamp is still above us"*). But in all subtasks combined, Nick drew uniform light propagation in the reference frame of the graph paper. Nick also evaluated this new light propagation relative to the lamp-room frame: Light moving to the left had a speed of three squares per time unit, relative to the lamp-room frame. When prompted, Nick argued that this answer is not consistent with the constant value of two squares per time unit for the speed of light.

Two other participants changed reference frames for light propagation because they experienced conflict between their answer and the speed of light as the maximum speed in nature. We will illustrate this with the case of Sanne. Initially, Sanne drew and reasoned consistently with a reference frame of the lamp-room frame. She explained that, although in subtask B1 the observer moves, and in B2 the room moves, there is no difference between the outcomes of the two subtasks. However, when she started working on subtask B3, she expressed that the moving room did influence the task outcome:

> ***Sanne**: OK, it does matter, but I do not really know how. [..] I don't really know how to continue with that.*

Sanne proceeded with subtask B3 and still drew light in the reference frame of the lamp-room frame. The researcher asked her to reflect on the results. In this, she evaluated light propagation in the frame of the graph paper, which resulted in a value for light propagation that exceeded the speed of light. This result seemed to confuse her, and she expressed that there is a conflict between her answer and the speed of light as a maximum speed. She repeated three times that this was problematic:

> ***Sanne**: Yes, that cannot be higher, nothing can become higher than the speed of light, at least that is what I have heard all my life, ehm…*

Eventually Sanne changed her answer in both subtasks B1 and B3. If Sanne would have adopted the light postulate instead of the paper reference frame, there would still be a conflict between the speed of light as maximum speed and the task outcome of subtask B2. Sanne did not express any conflict with this subtask. We therefore conclude that she indeed switched to the paper frame.

Flexible use of reference frames

Evaluating the speed of light in a different reference frame than the light propagation frame of the participant, is not unique for those students who change light propagation frames. This reasoning was also observed with six participants who stayed with their initial propagation frame. For these participants, evaluating light speed in other reference frames does not lead to a conflict. We will illustrate this with two examples. Niels uses the graph paper frame and Tim uses the lamp-room frame. Both students also evaluate the speed of light relative to the observer.

> ***Niels**: Because here [B2, light that goes to the left] you walk along with the speed of light, so relative to you it will go slower. It is the same idea as when you bike along with a car. If you bike away from the car, it will go away faster, for your idea, then when you bike along. So, for your idea light will go faster to the right.*

> ***Tim**: The light still covers the same distance. Say, in real life, light goes with […]$3{\cdot}10^8$ m/s and if you also go with $3{\cdot}10^8$, and if you move away from the light with that speed, then you move, and the light moves, but you will never see it, because it will never get closer, or it will never go further away, although you both move […] Yes, if you*

> *leave one second earlier [than the light flash] and you move just as fast, you will never see it.*

Niels used an informal method of Galilei-transformation to evaluate the speed of light relative to the observer. In this example Tim returned to measuring the distance light covers, and that this distance will still be the same independent of reference frame.

These results show that the students use several reference frames to describe the speed of light in. Only, there is just one reference frame in which the speed of light is uniform and equal to the set value of two squares per time unit. This suggests that participants have the tendency to think that movement was more real in one reference frame and just apparent in others. This reference frame coincides with the frame for uniform light propagation.

Combination of two reference frames

One participant did not fit one of these categories. This participant was also focused on what is moving, similar to participants who reason in the reference frame of the graph paper. However, the speed of light drawn in the EDs is not constant in one reference frame. Light that travelled in the propagation direction of the light source moved with two squares relative to the lamp. The participant explains this by saying that the light is pushed by the light source. Light travelling in the opposite direction had a speed of two squares per time unit relative to the graph paper. The participant said this light is left behind and that the illuminated area is growing.

3.4. Conclusions

The purpose of our study is to find out in what ways students reason with light propagation in relativistic situations prior to instruction. We found that all but one of the participants could work with EDs. We therefore conclude that students can learn to productively use EDs as a reasoning tool. We found one participant who reasoned with an absolute speed of light. This participant had already learned SRT. The other participants reasoned with a uniform speed of light relative either to the lamp or to the graph paper, in line with our expectations. We therefore conclude that secondary education students do reason with light propagation in one of two alternative reference frames.

These students consistently use this reference frame, in all subtasks. Most importantly, this study showed that many students not only evaluate the speed of light relative to their preferred reference frame for uniform light propagation, but that they also are able to do this relative to other reference frames. The students are aware that light travels at a different speed in these other frames, but most students do not spontaneously see this as problematic. Some students did experience a conflict when comparing light propagation in several reference frames, which led them to change their reference frame for uniform light propagation.

3.5. Discussion and implications for education

This study was intended to gain input for designing SRT education and therefore had an explorative character. Although we cannot claim an exhaustive overview of all possible reasoning patterns and their frequencies, we argue that the 15 in-depth interviews did yield new insight into student reasoning on light propagation in relativistic situations and form a sufficient basis for a well-founded design of SRT education.

A possible objection against our findings could be that the reference frames the students use for uniform light propagation are induced by our external representation, the ED. EDs are always drawn from one specific reference frame or observer (Scherr, 2001). It is impossible to create EDs that do not favour one reference frame over another. However, we created the EDs in this study to show the same situation portrayed from different reference frames. The task design allowed the students to describe uniform motion in three reference frames: The graph paper, the room, and the observer. Although the EDs allowed the students to draw light propagation in a specific reference frame over the subtasks, one of the participants still did not reason with light propagation in one specific reference frame. We therefore conclude that our task design did not force students to use a reference frame for the speed of light at all. Furthermore, our data showed variance in the reference frames participants chose uniform light propagation. We therefore conclude that the task design did not force students to favour one reference frame over the others.

Previous studies suggest that students do have difficulty describing the same situation from different reference frames, and that these difficulties should be overcome by more or better education of Galilean Relativity (Scherr et al., 2001; Scherr et al., 2002; Villani & Arruda, 1998). By contrast, the participants in our sample showed great flexibility in using reference frames. They could describe the speed of the observer, room and light relative to several reference frames (the paper, lamp, and observer). These results indicate that switching between reference frames itself is not problematic. In contrast with

SRT, where the speed of light is absolute, in Galilean Relativity the speed of light is different in each reference frame. Therefore, focusing on Galilean Relativity alone might not help students overcome their difficulties with the light postulate.

Although both students and physicists may agree that the speed of light is constant, students give a different meaning to these words. It seems as if students think that “the same for all observers” means that all observers will agree on a value for light speed, but that this value is not the same *relative to all* inertial observers. For physicists, “the same for all observers” does mean that all inertial observers will measure the same value for light speed in their own reference frame. Education should make students aware of this difference between agreeing on the same value and measuring the same value in all inertial frames.

The fact that most of the students in our sample reason from multiple frameworks, and that some even change their way of reasoning with light propagation, leads us to expect that explicitly problematizing alternative reference frames for light propagation in this way may also be a promising approach for teaching the light postulate. EDs allow students to make their ideas on light propagation explicit, constructing their ideas step by step, and to reflect on those ideas. Therefore, EDs seem a promising tool to support students in problematizing alternative reference frames for light propagation. Whether or not this approach will also convince students of the light postulate itself is the topic of our next study.

Chapter 4

An Educational Reconstruction of Special Relativity Theory for Secondary Education

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Abstract – Einstein's derivation of Special Relativity Theory (SRT), based on hypothetical reasoning and thought experiments, is regarded as a prime example of physics theory development. In secondary education, the introduction of SRT could provide a great opportunity for students to engage in physics theorizing, but this opportunity is largely being missed in current teaching practice. One reason could be that secondary students lack some knowledge of electromagnetism that was central to Einstein's argument. Therefore, we conducted an Educational Reconstruction to develop a teaching approach that would not rely on advanced understanding of electromagnetism, yet retains the modes of reasoning that were characteristic of Einstein's approach. In our reconstruction, we identified the light postulate, which is notoriously difficult for students to grasp, as a central concept. We developed a teaching and learning sequence in which students perform relativistic thought experiments and try different interpretations of the light postulate. Through these activities, students are expected to experience how the new concepts meet the requirements for a good theory. Experimental evaluation of the teaching and learning sequence indicates that this can be a fruitful approach to introduce SRT to pre-university upper-level secondary students.

Key words – Special Relativity Theory, Model of Educational Reconstruction, Secondary Education, Thought Experiments, Teaching and Learning Sequence

4.1. Introduction

Special Relativity Theory (SRT) has recently been introduced to secondary physics curricula in several countries. One of these countries is the Netherlands, where SRT became part of the pre-university level physics curriculum in 2014. The theory has an iconic, pop-culture status among the public, which might inspire enthusiasm and curiosity in future learners. More importantly, SRT revolutionized the way physicists look at the world and is a prototypical example of theory development in physics. Therefore, SRT is a promising topic to familiarize students with physics as a process of scientific knowledge development, a key element in the history and philosophy of science. Science education aims for students to gain insight in the process of theory development, in addition to the aim for conceptual understanding (College voor Toetsen en Examens, 2018; National Research Council, 2012; OECD, 2013). However, this opportunity is not seized in the conventional textbook presentations of SRT, and little is known about how to achieve this.

Although SRT provides a prototypical example of physics theory development, its introduction may be challenging for secondary students. First, the historical reasons why SRT was introduced and how the theory was developed draw on prior knowledge that is not generally part of the secondary curriculum. Furthermore, the abstract and counterintuitive concepts and outcomes of SRT are difficult to learn (Gousopoulos, Kapotis, & Kalkanis, 2016; Hewson, 1982; Scherr, Shaffer, & Vokos, 2002; Villani & Pacca, 1987). SRT represents a transformation in physics, giving radically new meaning to existing concepts. Among other things, the theory replaced the classical concepts of an absolute time and space with an observer dependent spacetime. Gaining a type of knowledge that requires the learner to revise their basic assumptions is notoriously difficult and often leads to misconceptions (Vosniadou, 1994). Therefore, in a teaching and learning sequence (TLS) it is important to explicitly connect to students' prior knowledge, and support them in giving new, relativistic interpretations to familiar concepts (for example Amin & Levrini, 2017; Driver, Asoko, Leach, Scott, & Mortimer, 1994; Kattmann, Duit, Gropengiesser, & Komorek, 1996; Posner, Strike, Hewson, & Gertzog, 1982; van Oers & Wardekker, 1997; Vosniadou, 1994).

To design such a TLS, we found a productive tool in the Model of Educational Reconstruction (MER). MER provides a design frame to bridge the gap between students' ideas and physics concepts (Duit, Gropengiesser, Kattmann, Komorek, & Parchmann, 2012; Komorek & Duit, 2004). To this end, the model focusses specifically on the history and philosophy of physics to inform the educational design. Therefore, this design framework fits our learning aim with its dual focus on both conceptual understanding and the development of physics theories. (For a more extensive discussion on MER, see Section 4.2.1).

In this chapter, we present an educational reconstruction of SRT and a first proof of principle of the resulting teaching approach as an answer to the following research question:

> *How can learners in secondary education develop a conceptual understanding of SRT through engaging in a process of physics theory development?*
>
> a. *How can the key ideas and theory development of SRT be reconstructed into a content structure for instruction?*
>
> b. *To what extent can a TLS based on the aforementioned content structure be successful in bridging student ideas and physics concepts?*

The first sub-question will be answered in Section 4.2. After a brief presentation of MER, we will present our analyses of SRT from both the theory and the student perspective, resulting in the reconstructed content structure of SRT for secondary education. The second sub-question will be answered in the third and fourth section. The third section describes the teaching and learning sequence based on the proposed content structure and the rationale how the design may contribute to our overall learning aim. The fourth section describes the empirical evaluation of the design, illustrating whether the expected learning is also observed in a practical situation. We will conclude with answering our main research question and discussing some of the implications of this study.

4.2. Educational Reconstruction

4.2.1. Model of Educational Reconstruction

MER is a specific approach to design research. Specific for this approach is that the educational design is informed both by an analysis of the theory and its history, and by an analysis of the learners' perspective in an iterative design process (Duit et al., 2012; Komorek & Duit, 2004). Figure 4.1 shows how the analyses of the theory perspective and the learners' perspective mutually influence each other and the design and evaluation of learning environments in an iterative process.

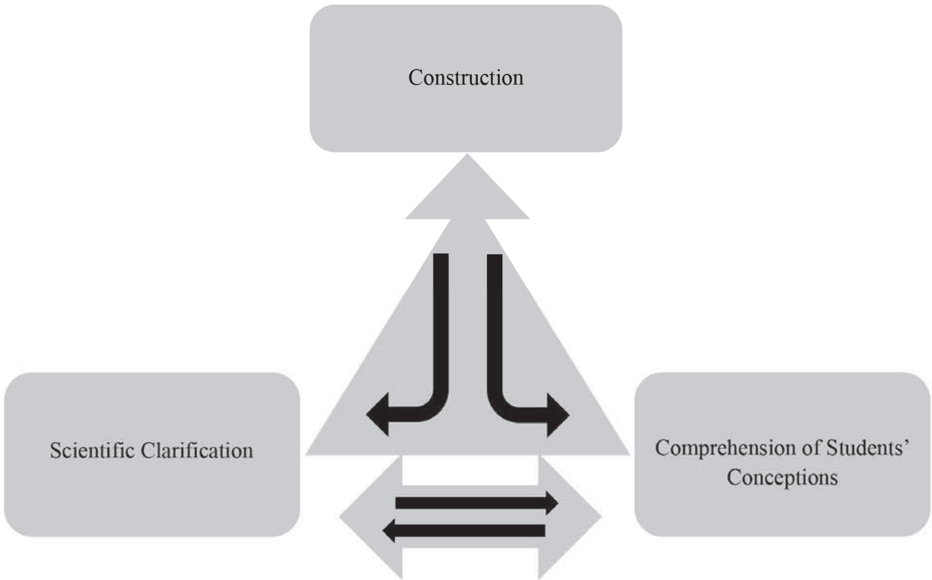

Figure 4.1 The three components of research of the Model of Educational Reconstruction

The analysis from the theory perspective aims to clarify the conceptual structure of the domain and to help identify the key insights to be attained from the perspective of the overall learning goal. Analysis of the history and philosophy of the domain can help to identify likely conceptual hurdles, and ways of overcoming them.

The analysis of the learners' perspective aims to identify relevant prior knowledge and learning difficulties for the core elements of the theory. In addition, this analysis also seeks out successful approaches to overcome these difficulties. To this end, we will draw on the available research literature.

The previous analyses result in a breakdown of the theory in its basic elements and learning difficulties with these concepts, and ways to overcome them. The reconstruction rebuilds the theory from a learners' perspective, resulting in a content structure for instruction. This content structure serves as a guide for the conceptual development of the learner towards the relativistic concepts. This reconstruction serves as a starting point for an educational design and its evaluation.

In the following sections, we will first report our analysis from the theoretical perspective, and the learner perspective, in order to attempt an educational reconstruction in Section 4.2.4, which will be built of insights from both perspectives.

4.2.2. Analysis from the theoretical perspective

Here we present an analysis of the theory from the perspective of the overall learning goal. The Dutch curriculum describes the following learning goal for SRT: *"The candidate can explain the phenomena of time dilation and length contraction, using the concepts of light speed, reference frame and simultaneity, in the contexts of thought experiments and applications"* (College voor Toetsen en Examens, 2018, p. 32). We will take this aim as a starting point for our analysis. The emphasis on explaining relativistic phenomena invites a conceptual approach. Therefore, we will in addition aim to contribute to students' scientific literacy by reflecting the process of theory development in our design. To these ends, we will identify the basic principles of SRT and analyse the reasoning that led to these principles and the theory itself. In our analysis, we build upon insights from the philosophy of sciences, in particular the work by Lakatos (1976), which will be outlined below, and the styles of scientific reasoning described by Kind & Osborne (2017).

The process of students constructing a new understanding can bear interesting similarities to the process the scientific community went through in accepting the original idea (for example Gopnik & Wellman, 2012, Posner et al., 1982; Vosniadou, 1994). Posner et al. (1982), for instance, described how their theory of conceptual change was similar to the process of scientific theory development as described by Lakatos (1976). Lakatos argues that scientific theories can be regarded as part of a research programme in which the successive theories constitute a consistently progressive theoretical shift over their predecessors (Lakatos, 1976). New theories are accepted in the scientific community because of this progressive theoretical shift. According to Lakatos, such theories meet five requirements:

1. There is a need for a new way of looking at the world;
2. The new theory is plausible and intelligible;
3. The new theory solves the problems that cause the need to look at the world in a new way;
4. The new theory confirms what is already known; and
5. The new theory leads to a fruitful research programme.

Posner argues that, although there are many differences between scientific experts and novices, there can also be fruitful parallels, in that both scientists and students will tend to stick to their old ideas, and they will only change to a new idea if specific conditions have been met. Therefore, educational designers may find helpful clues in the history and philosophy of physics to help students bridge the gap between their pre-instructional ideas and physics concepts (Kattmann et al., 1996; Levrini, 2014). This is not to argue that the history of science should be replicated in the classroom, but rather that clues from history and philosophy can be one element to inform the educational reconstruction of the material. In our case, we are searching for an educational reconstruction that will retain the essential characteristics of the reasoning process that led to the development of SRT. As Kind and Osborne (2017) argued, each discipline has its own characteristic style of reasoning. They propose six characteristic styles to deserve a place in secondary education: Mathematical deduction, experimental evaluation, hypothetical modelling, categorization and classification, probabilistic reasoning and historical-based evolutionary reasoning. We propose that the frameworks proposed by Lakatos and by Kind and Osborne can be helpful to capture the essential feature of the process that led to the development and acceptance of SRT. Therefore, we will use these frameworks as a lens to analyse the development of SRT as presented by Einstein.

SRT builds on two existing theories: Maxwell's electrodynamics and Galileo relativity. In the paper "Zur Elektrodynamik bewegter Körper" (Einstein, 1905), Einstein addressed a mismatch between the principles of Galilean relativity and the interpretation of Maxwell's electrodynamics. From this mismatch, which Einstein referred to as an asymmetry, he inferred the need for a new way of looking at the world:

> *It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. (Einstein, 1905/1952a, p. 37)*

The asymmetry Einstein referred to pertains to the phenomenon of induced current in a coil. When a permanent magnet moves relative to a coil of conducting material, a current will be induced in the coil. This process can be described from the reference frame of a stationary coil with a moving magnet, or from the reference frame of a stationary magnet with a moving coil. The induced current is the same from both perspectives. That natural phenomena are independent of the reference frame you describe them from was widely accepted in classical mechanics. Galileo described in his theory of relativity that the mechanical phenomena on a ship are not affected by its state of motion. Moreover, it was widely accepted that the theoretical explanations causing these phenomena are also independent of reference frame, i.e., the laws of mechanics are invariant under transformation to a different (inertial) reference frame. One would expect, as Einstein did, that the mechanics causing the current to run in the coil is also independent of the choice of reference frame. However, the interpretation of Maxwell's theory in Einstein's time was different. If the phenomenon was described from the frame of the stationary coil and the moving magnet, the current was caused by an induced electric field and thus an electric force, and if the phenomenon was described from the frame of the stationary magnet and the moving coil, the current was caused by a magnetic force. Einstein argued that there is no reason in the observed phenomena to accept this theoretical difference:

> *Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good. (Einstein, 1905/1952a, pp. 37-38)*

Here, Einstein introduced his epistemic conviction that there is a need to describe the world in a new way (Requirement 1), which can be interpreted as a desire for symmetry or unification: Not only should the laws of Mechanics be invariant under transformation, Galilean relativity should be expanded to the domain of Electromagnetism and Optics (Abiko, 2005). The new theory should solve the asymmetries in Maxwell's Electrodynamics Einstein referred to. To this end, Einstein introduced a new way of describing light propagation, the light postulate:

> *We will raise this conjecture (the purport of which will hereafter be called the "Principle of Relativity") to the status of a postulate, and*

> *also introduce another postulate, which is only apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body. These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies. The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here to be developed will not require an "absolute stationary space" provided with special properties, nor assign a velocity-vector to a point of the empty space in which electrodynamics takes place. (Einstein, 1905/1952a, pp. 37-38)*

From the current perspective on Maxwell's electromagnetism, the light postulate does not seem a far stretch. However, it was revolutionary in Einstein's time. From Maxwell's equations follows an electromagnetic wave that propagates with a velocity c. Experiments performed by Hertz had demonstrated that light had electromagnetic properties, and therefore the electromagnetic wave proposed by Maxwell was interpreted to be light. However, the theory did not specify a reference frame for this wave. Before Einstein, light propagation was considered as a mechanical process, and light velocity was implicitly or explicitly defined relative to a source or a medium. Newton, for instance, considered light to have a corpuscular nature (Newton, 1730/1952), implying a constant speed relative to the light source. In this model, light is described as a stream of tiny particles. By contrast, Huygens compared light propagation to sound waves (Huygens, 1690/1952). This wave-like model describes light as a mechanical wave propagating with a constant speed relative to a medium or rest frame. 19th century physicists assumed a medium was needed for electromagnetic waves as well: The luminiferous ether.

However, about twenty years before Einstein's work, the attempt by Michelson and Morley to demonstrate the movement of the earth relative to this medium had failed: They could not detect evidence of relative movement (Michelson & Morley, 1887; Lorentz, 1895/1952a). Einstein referred to this experiment as "unsuccessful attempts" to prove the existence of the luminiferous ether[1]. He proposed to follow Maxwell and to break with the practice of specifying a reference frame relative to which the speed of light is

[1] Note that Michelson and Morley assumed the luminiferous ether was present, and solely aimed to establish the relative movement of the earth to this medium (Gim, 2016).

constant. Rather, he proposed the speed of light is constant, and equal to c, in all reference frames. It is therefore not surprising Einstein assumed the light postulate might seem contradictory for his audience. However, Einstein promised a “simple and concise theory” that would solve the mentioned asymmetries in (the interpretation of) Maxwell’s electromagnetic theory and expand it to the relativity principle. In our view, Einstein offered with this a plausible and intelligible (Requirement 2) argument to, at least temporarily, accept the light postulate to be true and find out if Einstein delivers on his promise.

Guided by the constraints of the relativity principle, Einstein derived his new theory from the light postulate *“[w]ith the help of certain imaginary experiments”* (Einstein, 1905/1952a, p. 40). He showed what the world would look like when we temporarily assume the light postulate to be true. This became especially clear in Einstein’s derivation of a new definition of simultaneity: He took a system of two inertial observers in relative motion, assumed the light postulate to be true, and used deductive reasoning to arrive at a new consistent definition of this concept. Likewise, other key concepts of the theory, such as observers, events, time and spatial coordinates were carefully defined in such a way as to comply with the postulates. From these concepts, Einstein derived a set of equations to transform coordinates in spacetime from one inertial frame to another. Einstein’s interpretation of these transformations combined the separate concepts of space and time into one unified spacetime. In addition, Maxwell’s equations are invariant under these transformations. Thus, SRT solves the asymmetry in the interpretation of electromagnetism by replacing Galilean relativity with a new relativity theory. With that, Einstein showed that the new theory solved the problems that caused the need to look at the world in a new way (Requirement 3).

In order to be accepted, the new theory should also satisfy the other criteria proposed by Lakatos. As it turns out, the theory agrees with what is already known (Requirement 4). The transformations that Einstein presented were previously derived by Lorentz to explain the findings of the Michelson-Morley interferometer experiment (Lorentz, 1904/1952b), and SRT converged to Newtonian mechanics in the limits of low speeds. Furthermore, SRT also offered leads to new lines of investigation (Requirement 5). New phenomena predicted by SRT invited experimental verification. This was true for example for the light postulate: The Dutch astronomer de Sitter concluded that light from binary star systems always reached earth at the same speed, independent of the speed of the light sources (de Sitter, 1913). These results corroborated SRT.

Besides, SRT turned out to be just the beginning, describing only the limited domain of inertial frames. In order to complete the theory for situations where acceleration and gravity do play a role, further theoretical efforts were needed, leading to the General Relativity Theory (Einstein, 1916/1952b). At its introduction, SRT was part of a lively scientific debate. The ultimate implications of the theory remained hard to accept for many prominent physicists, such as Lorentz (Klomp, 1997). Despite this, SRT was accepted in the physics community over previous ways of looking at the world (classical physics) because it meets the requirements for a good theory.

In terms of scientific reasoning styles, Einstein's introduction of SRT drew heavily on hypothetical modelling. The process of hypothetical modelling can be described in four stages. First, a model is proposed and temporarily assumed to be correct. For SRT, this is the light postulate. Second, the consequences of the model are derived. Einstein derived relativistic phenomena such as the relativity of simultaneity, time dilation and length contraction. In addition to the light postulate, he drew on the concepts of observer and inertial reference frame and deductive reasoning in thought experiments. Third, there was a reflection on this result. For SRT specifically, the epistemic value of the Relativity Postulate guided this process. More generally, for the reasoning style of hypothetical modelling, the value of a model as a heuristic tool, the explanatory coherence of the model and the limits to representational accuracy also contribute to accepting the knowledge claims produced. Finally, this reflection resulted in the acceptance or rejection of the model. SRT explained observed phenomena and provided solutions for known problems, which contributed to the acceptance of the theory and the light postulate, even before its experimental verification. This process illustrates that hypothetical modelling (and other styles of scientific reasoning) draws not only on theoretical concepts, but is also informed by procedures to come to a knowledge claim and epistemic values to guide the decision whether to accept the produced knowledge claims or not (Kind & Osborne, 2017).

The theory development that we want reflected in our design can be summarized by the reason for Einstein to introduce SRT, a seeming conflict between two theories and the desire of unification, and hypothetical modelling with the light postulate. The latter also reflects one of the central principles of SRT. These findings lead us to reformulate our learning aim for SRT to productive reasoning with the light postulate, which means students can use the light postulate to derive and explain relativistic concepts.

4.2.3. Analysis of the learners' perspective

Here we analyse the theory development and central principles of SRT from a student perspective. First, we will focus on how SRT and the postulates are introduced. Subsequently, we will show what problems students may encounter with the relativistic phenomena derived from these basic concepts. Finally, we will present some solutions for these learning difficulties. This analysis will provide us with leads for our educational reconstruction and design.

Introducing SRT Einstein introduced the need for SRT by addressing an asymmetry with the interpretation of Maxwell's electromagnetism and subsequently expanding Galilean relativity to hold for electromagnetism as well. This historical logic cannot be copied directly into the secondary classroom, for two reasons. First, students, at least in the Netherlands, will not have sufficient knowledge of electrodynamics (see: College voor Toetsen en Examens, 2018). Second, most students do not hold strongly to the relativity principle as a guiding principle for theory development (Bandyopadhyay, 2009; Panse et al., 1994; Pietrocola & Zylbersztajn, 1999). As we argued in Section 4.2.2, it is this epistemic feature of the relativity principle that is essential to Einstein's argument. Therefore, we need to find alternative phenomena that can give rise to a similar line of reasoning.

Light propagation Central to relativity and the introduction of relativistic concepts is productive reasoning with the light postulate. The light postulate is notoriously difficult for students of all levels of education. It is reported that students can recite the light postulate after standard instruction (Dimitriadi & Halkia, 2012; Guisasola, Solbes, Barragues, Morentin, & Moreno, 2009; Yildiz, 2012). However, it is also reported they cannot apply it (Gousopoulos et al., 2016), a prerequisite for productive reasoning. Instead, students use Galilean velocity addition, and they interpret *c* as the maximum speed that can be attained (Gousopoulos et al., 2016; Villani & Arruda, 1998). These studies show that students know that light has a constant speed, but they do not operationalize it in the formal way of SRT. Instead students reason with a spontaneous or pre-instructional model of light propagation. In a study by Kamphorst, Vollebregt, Savelsbergh, & van Joolingen, (2019) about students' pre-instructional ideas, secondary students were asked to draw constant light propagation, thinking from the perspective of an observer in various relativistic situations. Rather than drawing and reasoning with a constant speed of light relative to this observer, participants reasoned with a constant speed of light relative to the light source, or relative to a form of absolute space (Kamphorst et al., 2019). Similar ideas have been found after instruction in higher education

(Villani & Pacca, 1987). Therefore, it seems difficult to change these pre-instructional ideas.

Relative motion and intrinsic phenomena Relativistic phenomena such as the relativity of simultaneity, time dilation and length contraction only become apparent when interpreting the same events in two reference frames that are in relative motion. At first glance, relative motions do not seem problematic for students: Bandyopadhyay (2009) and Kamphorst et. al. (2019) found that students compare velocities of objects and compare reference frames or describe light propagation relative to different frames, using spontaneous Galileo transformation. However, Saltiel & Malgrange (1980) found that students also regard motion as a property of the object itself. Several studies on students' ideas of reference frames, movement and classical relativity found that students often compare real motion with a dynamical cause, to apparent motion (Panse et al., 1994; Ramadas, Barve, & Kumar, 1996; Saltiel & Malgrange, 1980) and that they often treat this apparent motion as an optical illusion (Panse et al., 1994; Saltiel & Malgrange, 1980) caused by viewing from another reference frame (Panse et al., 1994). Students also tend to regard other phenomena like length and duration as an intrinsic property of a process or object (Dimitriadi & Halkia, 2012; Gousopoulos et al., 2016; Hewson, 1982; Levrini, 2008; Saltiel & Malgrange, 1980; Scherr, Shaffer, & Vokos, 2001; Scherr et al., 2002; Villani & Pacca, 1987). Furthermore, Scherr et. al. (2001) found that students do not recognize that relativistic phenomena are a consequence of two frames in relative motion. Students tend to treat the relativity of simultaneity as a phenomenon that is independent of relative motion, or they think simultaneity is absolute, omitting the relativistic aspect all together. Students also tend to think that relativistic phenomena such as time dilation and length contraction are apparent and disappear when corrected for signal travel time (Scherr et al., 2001).

Working with reference frames To overcome the idea that concepts such as velocity, length and duration are an intrinsic property of an object or process, students need to apply the concept of reference frame. Scherr et. al. (2001) showed that graduate and advanced undergraduate students after an undergraduate SRT course, do not spontaneously apply the concept of reference frame to determine the time of an event. This may be explained by the problems students experience with the concept of reference frame itself. Students often associate reference frames with concrete objects and regard them as fixed to a physical object (Panse et al., 1994). It appears to be difficult for students to determine what makes a reference frame. Students tend to think that observers at the same position (also those in relative motion) share a reference frame and thus agree on times and order of events (Scherr et al., 2001). At the same time, students tend to think that two distant observers (also those that are not in relative motion) are always in different frames, and therefore do not agree on the time and order of events. This may be because students tend to think that reference frames are limited to the sensory experiences of an observer (Panse et al., 1994; Scherr et al., 2001). Things that cannot be seen by an observer, because they are blocked by another object or are far away, are not part of the reference frame of that observer. To address part of the difficulties with reference frame, Dimitriadi & Halkia (2012) used the phrasing “point of view” of a specific observer.

Comparing reference frames Special Relativity requires that students make clear distinctions between reference frames. The outcome of their reasoning, like the time interval between events or the order of them, depends on the reference frame the events are described from. It appears that students also tend to take this aspect of relativity in overdrive. Scherr et. al. (2002) reported that students tend to think that different reference frames represent different objective realities. This results in students thinking that an event that happens in one reference frame does not need to happen in another and justify this idea by referring to quantum mechanics. In addition, students tend to think that observers cannot exchange information with other observers (Scherr et al., 2002). Also, they have trouble with the notion of an intelligent observer who can correct for signal travel time. Students associate the time of an observer registering an event with the time the event itself occurred, thus ignoring signal travel time. This results in students thinking that events are simultaneous when observed at the same time, again not taking signal travel time into account. When students compare reference frames and do acknowledge that observers can exchange information, they still run into difficulties with time dilation and length contraction. Students tend to have an asymmetrical interpretation of these phenomena (Aslanides & Savage, 2013): The clock of observer B is running slow for observer A because of time dilation. SRT states that this should be the same the other way around since there is one preferred reference frame. However, students think that for observer B the clock of observer A will run faster.

Overcoming the abstract nature of SRT In short, students interpret relativistic phenomena as apparent, have difficulty relating them to a reference frame and do not correct for signal travel time. A complicating factor in addressing these difficulties is that Special Relativity phenomena are not directly observable to students. First, because SRT-predictions differ from their classical counterpart only at very high velocities, and second because Special Relativity does only apply to situations without acceleration or gravity. Therefore, relativistic phenomena are abstract in nature and difficult to imagine to students. Several authors have proposed that thought experiments (TEs) can help students to learn new, abstract concepts and to overcome conceptual barriers (Helm et al., 1985; Velentzas & Halkia, 2013). TEs are supposed to encourage students to explore the consequences of their ideas in an idealized context, and to make their reasoning explicit (Matthews, 1994). This approach could be well-suited for this topic because TEs played a key role in the introduction and communication of SRT (Einstein, 1961; Einstein, 1949).

Similarities TE and HM Performing a TE can be regarded as a specific form of hypothetical modelling (HM). The first stage of a TE is to describe a central question, an initial situation, and the rules to be applied. This is similar to defining a model in HM. In the second stage of the TE, the consequences of the basic principles are derived to answer the central question. This is analogous to using the model to make predictions in HM. Finally, the overall conclusions of the thought experiment are interpreted, analogously to reflecting on the predictions and deciding to accept or reject the initial model (Kind & Osborne, 2017; Reiner & Burko, 2003). Therefore, thought experiments seem a feasible way for students to engage in hypothetical modelling in the domain of SRT. We intend to use the TEs in this way.

Supporting the process of performing a TE To perform relativistic TEs, students have to keep track of many processes and a lot of information in their minds. Students have to reason with an absolute speed of light in the context of two moving reference frames and obtain the outcome of the TE. An external representation can support students in this process. The Event Diagram (ED) has been used successfully to this end (Kamphorst, Savelsbergh, Vollebregt, & van Joolingen, 2021a).

In conclusion, the historical line of reasoning, starting from an apparent contradiction in Maxwell’s theory, is not a suitable approach to introduce SRT to students. However, we expect that it is worthwhile to maintain the logic leading to the theory of SRT in our educational reconstruction. Moreover, the central reasoning portrayed in SRT, hypothetical modelling by performing (supported) thought experiments, can help students to gain insight in abstract concepts and productive reasoning with the light postulate. TEs can also help students to reconceptualize velocity as a property relative to a reference frame rather than an intrinsic property of the object itself; to compare reference frames while reasoning about events.

4.2.4. Reconstruction for secondary education

In this section, we will present the reconstruction of the key ideas and theory development of SRT into a content structure for instruction. This content structure will be aimed at students learning to reason productively with the light postulate, which means students can use the light postulate to derive and explain relativistic phenomena. We designed this reconstruction with a student in mind who does not hold the same strict epistemic values as scientists, but who does show an appreciation for a coherent world view and a commitment to developing a consistent physics understanding of the world. We expect students to prefer a model that can explain observed phenomena over a model that cannot; to recognize that if two models come to different predictions for the same phenomenon, at least one of them will not be correct; and to acknowledge that a more general model is to be preferred over a model with limited predictive value.

The development of SRT was driven by the inconsistency between two theoretical ideas; this was the reason to introduce the light postulate, which could be demonstrated to solve the inconsistency, and led to a fruitful research programme. Therefore, the key idea of our educational reconstruction of SRT is to derive relativistic concepts through productive reasoning with the light postulate. To that end, students need to regard phenomena in relation to reference frame, compare reference frames, and reason in context of high relative speeds. To reconstruct the key ideas and these aspects of the theory development of SRT into a content structure for secondary education, we formulated three principles that served as guidelines for our design. We propose these principles can contribute to productive reasoning with light propagation for secondary students. The design should enable students to experience:

1. A need for a new light propagation model, i.e. the light postulate, and that this need is plausible from their perspective,
2. That the light postulate solves the problem introduced by the need for a new propagation model and this new model leads to a fruitful research programme, and
3. The process of theory development of SRT through hypothetical modelling activities.

The literature analysis showed that the issue about Maxwell's equations that originally gave rise to the development of SRT is not suitable as a context for secondary education. In addition, the analysis showed that introducing the light postulate by defining it does not result in students reasoning with it. They tend to fall back to a pre-instructional light propagation model. This student model can be described as a constant speed relative to something: The light source or the background (Kamphorst et al., 2019). If we describe the absolute speed of light of the light postulate in the same terms, this is a constant speed relative to all inertial observers.

We propose that students can appreciate the need for a new light propagation model once they attain the following insights:

1. (Pre-instructional) light propagation always is relative to a reference frame;
2. Different choices for this reference frame are possible;
3. Predictions differ dependent on the choice of reference frame; and
4. Their current reasoning leads to wrong/inconsistent predictions.

Once these insights have been attained, they may start questioning their choice of frame, which makes it plausible to introduce a new propagation model. To subsequently start and continue to reason productively with the light postulate, we propose that students need to:

5. Change the reference frame for light propagation to the reference frame of the observer;
6. Experience that this new light propagation model solves the problems they experienced with their pre-instructional models; and
7. Explore the consequences of this new propagation model.

We have addressed these two phases of theory development (1-4 and 5-7) in the two parts of our educational design, illustrating how the key ideas and theory development of SRT can be reconstructed into a content structure for instruction.

Part 1: Introducing the need for a new light propagation model - Becoming aware of the limited predictive value of pre-instructional light propagation models

We expect that hypothetical modelling with their pre-instructional model in carefully designed tasks, can create a need for students to start reasoning with the light postulate and follow the epistemology of the theory development of

SRT. The two initial models that most students use correspond to light propagation models physicists held in the past: A wave-like and a particle-like model (see Section 4.2.2). Since students' initial models tend to be fluid over different contexts (DiSessa, 1996), they are named as these corresponding physics models. This is to ensure both models are addressed, students mean the same when referring to a model, and to stimulate students to reason consistently with the models over different contexts. In addition, a formal model provides common ground and can also be used correct or wrong, whereas a student model is correct by definition. Consistent reasoning will lead to different predictions for each model in contexts with relative movement between light source and observer. By comparing these results to findings from historical experiments, students can experience that both models are inconsistent with empirical findings and therefore have limited predictive value. We expect this inconsistency will provide sufficient reason for students to question the reference frame of both these formal models and, as a consequence, the reference frame of their own light propagation model.

Part 2: Developing confidence in the light postulate as a propagation model for productive reasoning

Students can solve the problem of the limited predictive value by proposing a "new" light propagation model: The light postulate, starting a second cycle of hypothetical modelling. Based on the outcome of the experimental evaluation, students can change the light propagation frame to that of the observer. Because of the introductory activities, this new model will be plausible for students and lead to conclusions that confirm what they already know. Subsequently, students can explore the consequences of the light postulate. We also expect that they can experience the reference frame dependence of relativistic phenomena by deriving these themselves. Moreover, this activity may also help students to accept these concepts and phenomena despite their counterintuitive nature because they can experience the phenomena are a consequence of the light postulate and relative motion.

Table 4.1 Content structure for instruction and how these conceptual steps relate to tasks in the hypothetical learning trajectory

Content structure for instruction	Hypothetical Learning Trajectory
Part 1: Introducing the need for a new light propagation model - Becoming aware of the limited predictive value of pre-instructional light propagation models	
HM with pre-instructional model	
1. Becoming aware of the initial light propagation model and the role of reference frame in this model;	Task 1: Exploring initial ideas
2. Becoming aware of other options for reference frame (through the introduction of formal models) and as a consequence questioning the reference frame of the initial model;	Task 2: Confronting inconsistencies
3. Becoming aware that the two formal models, and as a consequence the initial propagation model, do not have predictive value in all context (Requirement 1 of Lakatos);	Task 3: Evaluating predictions
4. Therefore rejecting the reference frame of these models and making it plausible to introduce a new model (Requirement 1 of Lakatos).	
Part 2: Developing confidence in the light postulate as a propagation model for productive reasoning	
HM with light postulate and exploring its consequences	
1. Proposing a new, consistent light propagation model which is therefore plausible: the light postulate (Requirement 2 of Lakatos);	Task 4: Resolving tension
2. Confirming the new model solves the problem of limited predictive value (Requirement 3 and 4 of Lakatos);	
3. Using the light postulate to make predictions in new contexts (Requirement 5 of Lakatos);	Task 5: Exploring counterintuitive consequences
4. Deciding to keep using the model;	
5. Deriving new concepts with the light postulate (Requirement 5 of Lakatos).	Task 6: Exploring the consequences of the light postulate for time

We acknowledge that the steps of hypothetical modelling by students may not all happen explicitly. For example, students can communicate their models by using them, and communicate they accept the models by continuing to do so.

The content structure for instruction that is the result of our educational reconstruction of Special Relativity Theory for secondary education is summarized in Table 4.1.

4.3. Hypothetical Learning Trajectory

In the previous section, we described a content structure for instruction that would provide students with a basis to reason productively with the light postulate. To test whether these steps would represent a feasible learning pathway, we designed a hypothetical learning trajectory - that is, a sequence of tasks and activities, each accompanied by hypotheses about what the student would learn, and how this learning would become evident from what the student says and does at that point.

The resulting HLT consists of six subsequent tasks, structured around two thought experiments. Each task consists of a reasoning activity supported with an Event Diagram, and a reflection on this activity. The current section presents the HLT, which will be subjected to empirical evaluation in Section 4.4 (Bakker, 2018; Komorek & Duit, 2004; Simon, 1995). Sections 4.3 and 4.4 together will answer the second sub-research question, whether a teaching and learning sequence based on the content structure for instruction can be successful in bridging the gap between students' ideas and physics concepts.

Part 1: Introducing the need for a new light propagation model - Becoming aware of the limited predictive value of pre-instructional light propagation models

This part introduces the need for students to change their ideas about light propagation. To that end, students engage in a sequence of hypothetical modelling tasks using different light propagation models. Each task offers opportunities to become aware of one's reference frame for light propagation and to start questioning this frame. Students will experience that both the "wave-like" and the "particle-like" model lead to inconsistent results. This finding may introduce the need for a new propagation model or make the need for such a model plausible. We do not expect all students to experience this need at the same moment, but we do expect that the three tasks together will introduce the need to reason in a new way with light propagation for all students.

Task 1: Exploring initial ideas

Aim Students become aware of their initial light propagation model and that this model is a constant speed relative to something.

Task Students are asked to imagine an observer who simultaneously receives two light flashes, coming from opposite directions, on his measuring device. The flashes are emitted by two lamps that are mounted on a moving cart, passing by the observer on the ground. The assignment for the student is to figure out at what time(s) the lamps emitted the light flashes. The initial settings of the task are shown in an Event Diagram (ED, Figure 4.2), a graphical representation of spacetime. The ED shows the position of objects, observers and events from a specific reference frame at subsequent moments in time. The bottom picture of Figure 4.2 shows the event of two light flashes arriving simultaneously at the observer. The position of the light flash at previous instances can be added by the student. This supports students' stepwise reasoning with light propagation in performing the task (Kamphorst et al., 2021a). In all tasks of our design, the speed of light in the ED is set at two squares per time unit. Students are free to choose a point of reference for measuring this speed. After performing the task, the teacher asks students how they constructed their drawings in the ED and how this portrays a constant speed of light.

Evidence of learning We expect students to construct a constant velocity either relative to the light source (Figure 4.2a) or relative to the background or graph paper (Figure 4.2b) (Kamphorst et al., 2019). When the task is performed with a constant speed of light relative to the lamp, the student will predict that the right lamp emitted a light flash at t = -2. The second approach predicts that the light flash was emitted at t = -4. The task outcome and how this outcome is obtained, shows students' pre-instructional light propagation model. We expect that the ED supports students in reflecting on their task performance because the ED provides them with a "written" account of their reasoning. We expect that explaining the consistency of their pre-instructional light propagation model makes students aware of this model and that such a model consists of a constant speed relative to something (the lamp or the graph paper). They may show this by mentioning the element in the ED relative to which the speed of light is constant: Relative to the lamp, or to the graph paper. By performing and reflecting on this task, students engage in the first two steps of hypothetical modelling: They use a pre-instructional model to make predictions and explicate this model by explaining it to the teacher. If both initial models have been mentioned in the classroom discussion, students might even recognize they can choose between these light propagation frames.

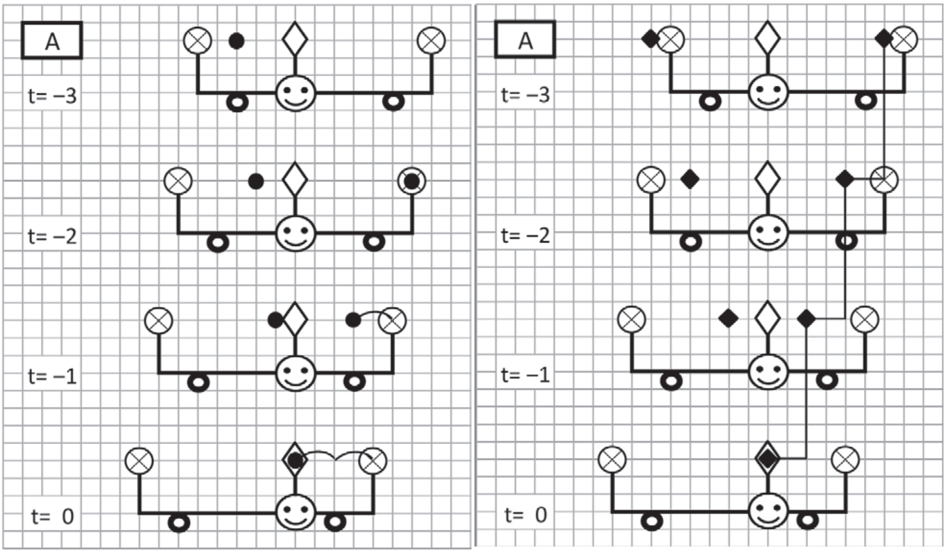

Figure 4.2 ED to support Task 1. The figure shows the position of a cart with two lamps (lamp symbol: Circle with cross) attached to it at four subsequent timesteps. The light flashes emitted by the lamps reach the measuring device of the observer (smiley) simultaneously at $t = 0$. The position of the light flash is drawn with dots for two initial light propagation models. Figure 4.2a (on the left) shows a constant propagation relative to the light source (solid dots); Figure 4.2b (on the right) constant light propagation relative to the graph paper (solid diamonds)

Task 2: Confronting inconsistencies

Aim Students engage in hypothetical modelling with two formal propagation models relative to two reference frames and as a consequence start questioning the frame of their initial propagation model.

Task The teacher introduces two formal propagation models based on the ideas of Newton and Huygens.

> **Newton – particle-like model** Light propagates with a constant speed relative to the light source. This model is similar to the first student model (Figure 4.2a).
>
> **Huygens – wave-like model** Light propagates with a constant speed relative to a medium or rest frame. The graph paper in the ED can function in the role of medium or rest frame. This model is similar to the second student model (Figure 4.2b).

The teacher points out the similarities between the formal models and the student models. Students are asked to repeat the previous thought experiment for each of the formal models. Next, they are asked to use these models in a similar thought experiment where both the observer and the lamps are on the moving cart (Figure 4.3b). Again, the two models will lead to different outcomes (Figure 4.3). When the task is performed with the particle-like model, students will conclude that the right lamp emitted a light flash at t = -4. The wave-like model will lead to the conclusion that the right lamp emitted a light flash at t = -7. The teacher reflects on two aspects of the task with the students. First, the teacher asks students to explain for each of the models how it represents a constant speed of light. Second, the teacher asks whether both models could be true at the same time. The teacher confirms that a choice between the models is necessary since an experiment cannot lead to two different outcomes at the same time.[2]

Evidence of learning We expect that both formal models are plausible for students and that they show this by using both models to perform the thought experiment. Furthermore, we expect students to acknowledge the similarities between their initial model and one of the formal models. Specifically, we expect that students can make the connection between the graph paper in the ED and the medium in the formal wave-like propagation model: The concept of medium in light propagation is part of the secondary curriculum. In addition, we expect students to recognize that both formal models are an example of a constant speed relative to something: Either the lamp or the graph paper. They show this by agreeing with the teacher when the models are explained, or by mentioning these reference frames when working with the models. Finally, we expect students to interpret that the two models lead to different task outcomes as that at least one of the models gives a faulty prediction. We expect students will express this by asking which of the two models is true or express a preference for one of the models.

[2] Some students may assume this is not problematic because of an incorrect interpretation of quantum mechanics. Although the famous double slit experiment in quantum physics confirms the wave nature of electrons or the particle nature when you look through what slit the electron goes, these two different outcomes refer back to two different executions of the experiment. One execution can only confirm one of the models. We do not expect our participants to experience this confusion because the topic of quantum mechanics was not covered previous to our intervention.

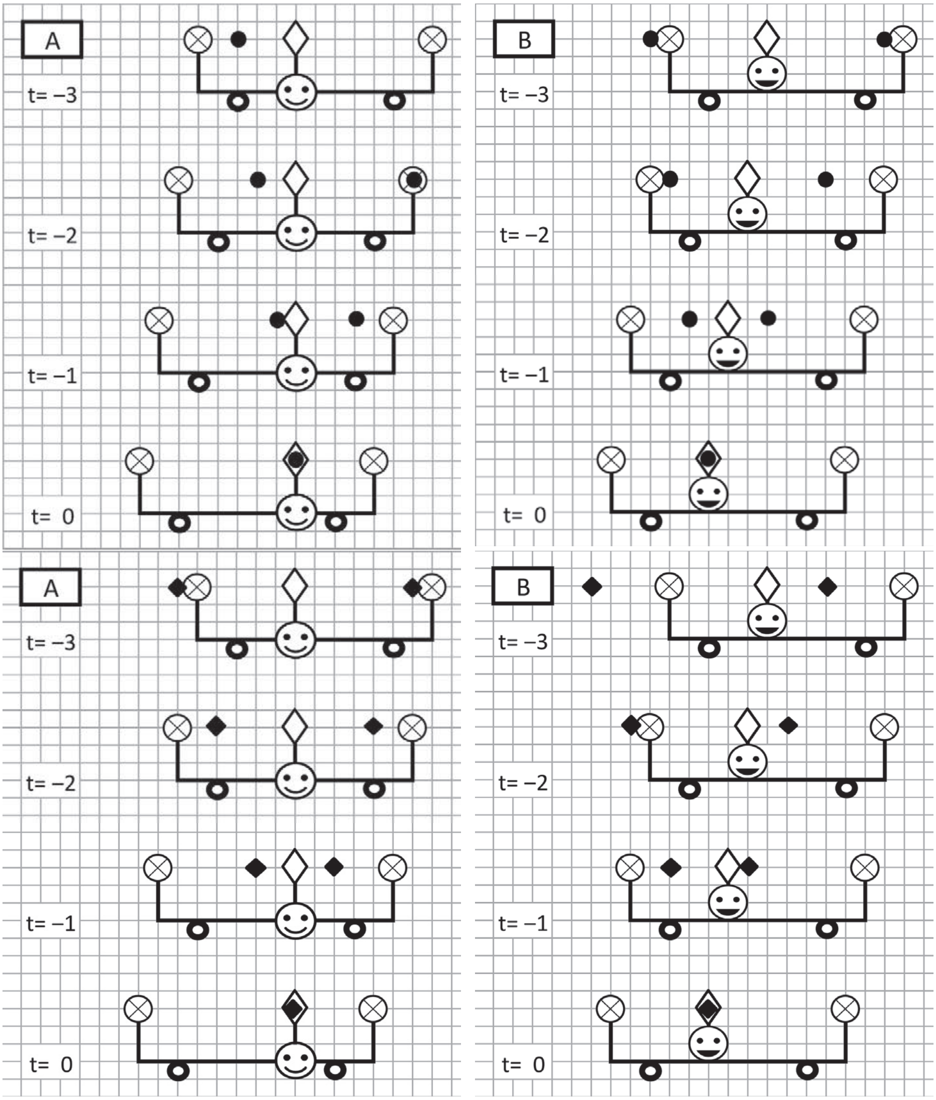

Figure 4.3 EDs to support Task 2. Figures 4.3a (top left) and 4.3b (top right) show the task outcome drawn with the particle-like propagation model (dots); Figures 4.3c (bottom left) and 4.3d (bottom right)with the wave-like propagation model (diamonds). Each model gives a different task outcome

Task 3: Evaluating predictions

Aim Students become aware that the two formal models have limited predictive value and, as a consequence, reject the reference frames of these propagation models and find it plausible to look for a new propagation model.

Task Students are presented with the outcome of two experiments: The De Sitter experiment (DSE) and the Michelson Morley experiment (MME). Students are asked to identify which experiment corresponds to what version of the thought experiment in Task 2. To support students in making this connection, they analyse the relative movement between the observer, light source and space or graph paper in both the EDs and the experiments. Once students linked the experiment to the corresponding ED, students are asked to use the outcome of the experiments to confirm or reject the predictions made with the formal models.

> **DSE** De Sitter observed light from a binary star system, two stars spinning around a common centre of mass. The outcome of this experiment was that all light *arrives* at the same speed, independent of the direction of movement of the light sources.

The DSE corresponds to ED A as in both situations a stationary observer receives light from two moving light sources. The findings of the DSE correspond to predictions of the wave-like model (Figure 4.3c) and not with those of the particle-like model (Figure 4.3a).

> **MME** Michelson and Morley measured light from stationary sources while the entire setup moved through space in our planetary orbit. The outcome of this experiment was that light has the same speed, independent of the direction in which the experimental setup moves through space.

The MME corresponds to ED B, as in both situations the observer is at rest relative to the light sources and this system moves relative to the supposed ether. The findings of the MME correspond to the predictions of the particle-like model (Figure 4.3b) and not with those of the wave-like model (Figure 4.3d).

Therefore, each formal model is not supported by the outcome of one of the experiments. This overall conclusion provides students with a rationale to reject these propagation models for light. As a consequence, there is a need to introduce a new propagation model. To underline this unexpected overall conclusion of the task, the teacher makes the conclusion formal: *Neither formal propagation model gives a coherent description for light propagation that leads to predictions that are confirmed by both experiments in the two situations.*

Evidence of learning We expect students to describe the relative movements in the EDs and we expect this will help them to recognize the similarities between the thought experiments and the DSE and MME. We also expect that students, with some help, can use the interpretation of the experiments to decide which predictions are supported by the experiment and which are falsified. We expect that students, with support from the teacher, will recognize that the task outcome means that neither of the formal models leads to correct predictions in *all* circumstances. These insights form the third and fourth step of hypothetical modelling: Evaluating the predictions and deciding to accept or reject the models. We expect this overall conclusion will introduce the need for a new light propagation model and will make it plausible for students to propose such a model. In addition, we expect the results confirmed by experiments (shown in Figure 4.3b and c) to provide students with tools to propose such a model. These expectations are confirmed when students can perform the tasks in Part 2 of the HLT.

Part 2: Developing confidence in the light postulate as a propagation model for productive reasoning

This part builds on the outcomes of the tasks in the first part. Students use the results of Task 3 to propose a new propagation model with a constant speed relative to the observer: The light postulate. Subsequently, students explore the consequences of the light postulate in new contexts and gain insight in new relativistic concepts, showing they can indeed reason productively with this counterintuitive concept. We expect that students will develop an increasing confidence in the light postulate once they see that it leads to a fruitful "research programme."

Task 4: Resolving tension

Aim Students propose a new light propagation model and change their light propagation frame to that of the observer. Students recognize that the problems of the limited predictive value of the previous models is solved by this new model.

Task The previous task and the exercise on relative movement provided students with the necessary building blocks to propose the light postulate. Based on the DSE students should reject constant velocity relative to the light source. Based on the MME students should reject constant velocity relative to the graph paper. The teacher asks students to propose a propagation rule for light that will reproduce the results of Figure 4.3b and c. Subsequently, the teacher asks students to check if their new model indeed reproduces the results of the confirmed predictions in Task 3. To conclude the task, the teacher confirms the new propagation rule: *Light propagates with a constant speed relative to the observer in all situations.*

Evidence of learning Since the other options have been excluded, we expect students to propose the light postulate in their own wording, for instance: *Light has a constant speed relative to the observer.* This shows students engaged in the first step of hypothetical modelling with the light postulate: Proposing a model. We furthermore expect that students will be able to verify that the new model leads to the correct predictions for both the DSE and MME-results, solving the problem of the limited predictive value of the formal models.

Task 5: Exploring counterintuitive consequences

Aim Students use the light postulate to perform thought experiments that result in counterintuitive outcomes and discover that the time of an event depends on the reference frame of the observer.

Task Students are asked to find out at what instant the lamps emitted a light flash in two contexts. In the first context, the observer is moving relative to the lamps (ED C, see Figure 4.4a). In the second context, a second, stationary observer is introduced (ED D, see Figure 4.4b). Students are asked to solve the thought experiment for these observers. Both observers are midway between the lamps at the instant two light flashes arrive simultaneously. Consistent reasoning with the light postulate will lead to the conclusion that the lamps emitted a light flash at t = -2 and t = -6 for observer C, and that the lamps emitted the light flashes simultaneously at t = -3 for observer D. Therefore, the overall task outcome of this TE is that observers in different reference frames will assign different times to the same event. Even more, that events that are simultaneous in the reference frame of one observer, are not simultaneous in the reference frame of another one. Subsequently, the teacher asks students to explain the task outcome. When students explain how the light postulate leads to the task outcomes, they are confronted with the counterintuitive results. At the same time, explaining the relation between the context of the TE, the light postulate and the outcome, can help students to accept this counterintuitive outcome.

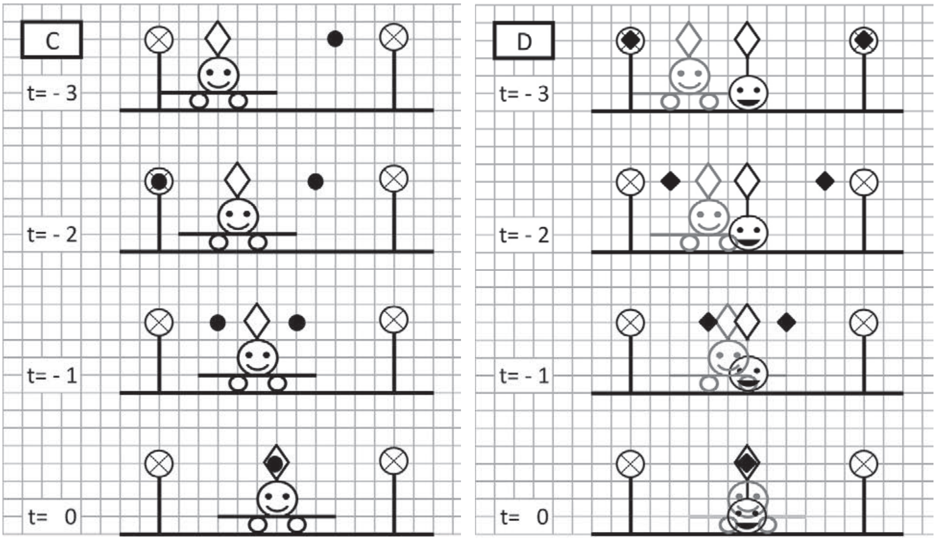

Figure 4.4 EDs to support Task 5. Light propagation is drawn with the light postulate for the observer on the cart (Figure 4.4a; on the left) and the one on the ground (Figure 4.4b; on the right)

Evidence of learning We expect students to perform the tasks with the light postulate, although some may fall back to their initial propagation model. If students fall back to their initial model, they will find that the lamps emitted their light flash simultaneously at t = -3 for both observers, independent of their initial model. Furthermore, we expect students to express they find these task outcomes counterintuitive. For instance, they would mention that the task outcome is strange. Despite this, we expect students can explain that this outcome is inevitable because the two observers are in relative motion and light has a constant speed relative to both observers. With this explanation, students would show they recognize the relation between the light postulate and the task outcome. Students therefore engage in the second and third step of hypothetical modelling: Using the model to make predictions and evaluate these predictions. We expect that the activity of explaining how the task outcomes are a consequence of the light postulate and the relative movement between the observers will help students to accept these counterintuitive outcomes. We expect that in turn, being able to explain the results will also contribute to students to keep using the light postulate in the next task, showing they accept this new propagation model, which is the fourth step of hypothetical modelling. Students may also express verbally that they accept this new propagation rule.

Task 6: Exploring the consequences of the light postulate for time

Aim Students reason productively with the light postulate by using the light postulate to derive the concept of time dilation and gain a conceptual understanding of this concept.

Task Students perform a version of the light clock thought experiment.

> **Light clock thought experiment** A light flash bounces up and down between two mirrors. Two observers study this process. The first observer is stationary relative to the mirrors. The second observer observes the mirrors moving relative to him.

Students are asked to find out how many timesteps the light flash needs to bounce up and down between the mirrors according to each observer. The thought experiment is supported with two EDs. Each ED is drawn from the reference frame of one of these observers (Figure 4.5). If students reason consistently with the light postulate, they will find that light travels vertically up and down relative to the observer studying mirrors in rest and that light travels a longer distance relative to the observer studying moving mirrors. Both light paths are represented in Figure 4.5. The overall outcome of this thought experiment is that light needs more timesteps to travel up and down in the light clock for the observer in ED F. To support students in obtaining the overall outcome of the task, the teacher asks them what the difference in path length means. The extent to which time dilation occurs depends on the relative velocity between the two observers. To reflect on this aspect, the teacher asks students how the duration would change in case the velocity between the observers increases or decreases.

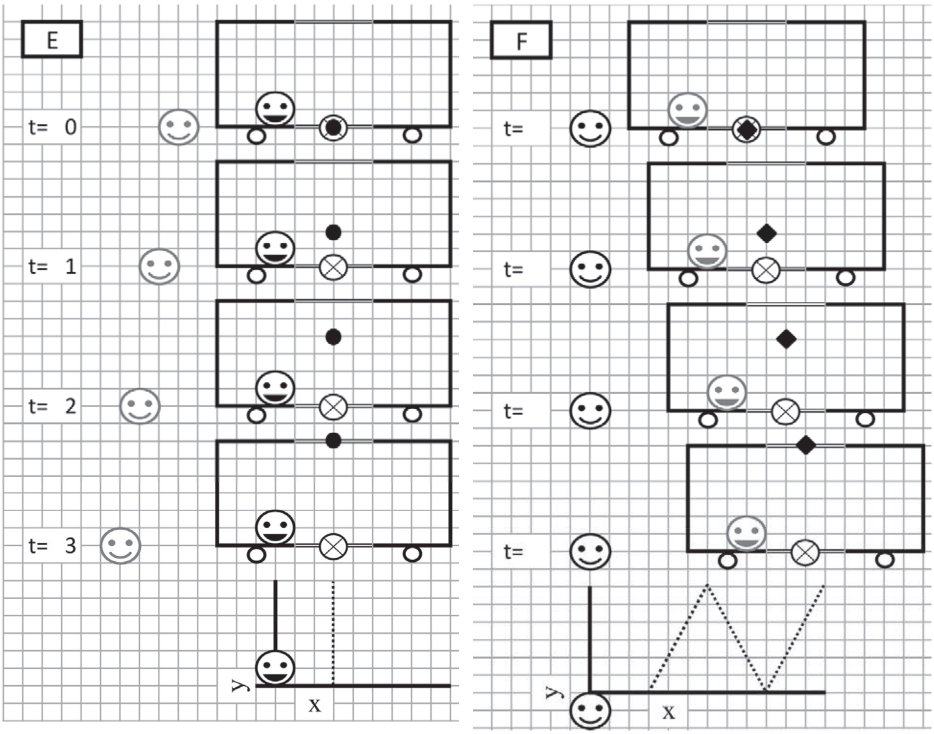

Figure 4.5 EDs to support Task 6. The figure shows a light clock drawn from two different reference frames. The light clock consists of two mirrors (horizontal dotted lines) and a lamp in the bottom mirror (symbol of lamp in electrical circuits). Figure 4.5a (on the left) shows the results when the light postulate is applied for observer A studying mirrors that are stationary in his frame (dots). Figure 4.5b (on the right) shows the same process for observer B who studies mirrors that are moving relative to his reference frame (diamonds). In that case, the speed of light relative to observer B is bigger than 2 squares per picture. Therefore, the timesteps are left blank

Evidence of learning We expect students to use the light postulate to interpret the outcome of the thought experiment. By doing so, students again confirm they accept this new model (step four of hypothetical modelling). We expect students to mention that light needs 6 timesteps to travel up and down between the mirrors for the observer studying the stationary light clock and we expect students to mention that light needs more than 6 timesteps to travel up and down for the observer studying the moving light clock. We expect students to conclude that the duration of the process is longer for the observer studying the moving system. In contrast, students who prefer the classical idea that time intervals are absolute, will say that light moves faster for this observer. We expect that students show they can interpret the consequences of relative velocity for the phenomenon of time dilation by mentioning that the effect of time dilation increases with increasing relative speed.

4.4. Empirical evaluation

4.4.1. Method

In order to test whether our approach would be feasible in principle, and to gain insight in possible student responses, we conducted an empirical evaluation with small groups of students, similar to the Teaching Experiment described by Komorek & Duit (2004). In such a Teaching Experiment, the researcher has a dual role of teacher and clinical interviewer. When student responses are unclear, the teacher will probe students' reasoning by asking for further explanation. In this study, our focus was on the functioning of the educational design, rather than individual student learning trajectories. To explore the potential of the teaching approach under optimal conditions, we worked with students who volunteered to participate outside regular class time. In order to gain a more complete picture of how the design can function in teaching practice, the experiment has been performed with multiple groups of students, and with students varying in proficiency levels (cf., Bakker, 2018; Komorek & Duit, 2004; Plomp & Nieveen, 2013a; Plomp & Nieveen, 2013b).

Participants In total, 30 students volunteered to participate in the research. All participants were 11th grade students in two different schools at the pre-university level, and had opted for the science track. Different versions of the design were performed with 12 groups in total, with each group consisting of 2-4 students. Groups were composed based on availability of the students at the given time slots. The experiment consisted of 3-4 lessons per group, lessons took place once a week in a free hour of the students. In this paper, we present data of the learning process of five groups (15 students in total) who worked with the final version of the teaching and learning materials as described in Section 4.3. The physics proficiency of the participating students as reported by their regular physics teacher is presented in Table 4.2. For the purpose of reporting, all students were given an alias. All students signed a consent form for participating in the study, collecting their notebooks and recording the lessons on video.

Implementation of HLT In this study, the first author takes the role of the teacher, following the teacher actions as described in the HLT as closely as possible. The students and teacher sit in a circle around a table. On the table, there is a central ED. The students also have individual notebooks and pencils. The tasks are presented verbally by the teacher. The supporting EDs are available in two forms: An individual notebook for each student and a bigger central version in which the students could collaborate. This central ED is placed on a portable whiteboard. The students can construct light propagation in this ED through placing small magnets in it. The intention of this central ED is both to stimulate collaboration and exchange of ideas between the students and to allow them to have a dynamic interaction with the representation. The individual notebooks are used to write down/draw the outcome of the collective effort.

Table 4.2 A short characterization of each group

Group number	Proficiency level in physics
Group A	Thomas and Martijn. Both belong to the most proficient students of their class.
Group B	Lisa, Daniel and Anne. Lisa is a proficient student, Daniels and Anne's proficiency is average.
Group C	Laura, Kevin and Iris. All students have an average proficiency.
Group D	Max, Sanne, Niels and Tessa. Niels is a highly proficient student. Max and Sanne are of average proficiency. Tessa has a low proficiency.
Group E	Kelly, Jeroen and Bart. Bart is a highly proficient student, Kelly and Jeroen have a low proficiency.

In an earlier version of the intervention, we only presented the students with EDs in individual notebooks in which they could draw light propagation. There were two drawbacks to offering only individual EDs. First, the students showed little interaction. Since a small groups approach had been chosen to stimulate student interaction, and to study student learning through their conversations, this was not a desirable effect. Second, the students lost track of their reasoning process due to crossing out little mistakes in their drawing. Therefore, we offered an extra ED to work on as a group in the final version of the intervention. We observed that the students were discussing their ideas with each other, while constructing light propagation in the ED. By offering the ED on a whiteboard the students could construct light propagation by placing tiny magnets in the diagram. This was also forgiving for small errors: Instead of crossing out a wrong drawing, creating a messy situation, the students could simply shift the magnet to the intended position and keep track.

Overall, participants were highly involved in the activities. The students had a good recollection of the previous lessons, considering a week with other lessons and homework had passed in the meantime. They could describe in detail what they did a week ago and what conclusions they had reached. The students were actively participating in the lessons and showed an interest in the materials. They were motivated to learn more about relativity and to participate in the study. Subsequently to the tasks described in the HLT, we spent some time with the students deriving the formulas for time dilation and length contraction. All students participated for the full 8 lessons of the HLT and these additional lessons in their free time, except for one student. This student had to quit after 5 lessons because of changes in his schedule. Since there was no reward for staying and no penalty for dropping out, this shows the students were committed to the study. SRT is one of 12 subjects in the Dutch upper secondary curriculum. The curriculum does not prescribe a specific number of lessons for each subject. Typically, teachers take 3-4 weeks per subject, which corresponds to 6-12 lessons. Our design fits well within these boundaries.

Data collection In order to gain insight in students' reasoning and learning processes, we need to analyse their utterances and actions. To that end, all lessons were recorded on video, and all student notebooks were collected. The camera was directed at the tabletop to register students working on the collective ED. Sound was recorded with a tabletop microphone connected to the video-camera. Video data were transcribed, and, for each group, the video and notebook data were combined into one comprehensive description of the lessons (data-triangulation, Denscombe, 2014).

Data analysis Subsequently, the descriptions were compared to the evidence of learning described in the HLT, to come to a description of actual student learning using a constant comparative method (Bakker, 2018; Cobb & Whitenack, 1996; Van der Wal, Bakker, & Drijvers, 2019). In this process, the HLT functioned as a theoretical guide to interpret student learning. With the HLT as a guide for comparing hypothetical and actual student learning, we first identified examples and counterexamples of the expected learning described in the HLT. In those instances of counterexamples of expected learning, we tried to identify clues in student interaction with the tasks thus far to explain why these student views would make sense from the student perspective. This analysis resulted in a detailed account of student learning at the group level, describing and interpreting if and how the hypotheses on student learning as described in the HLT were met. Each step in the process of describing and interpreting student learning was checked by a second analyst. This analyst studied the raw data material, and checked if the extended description was complete, and if subsequent interpretations were consistent with the data. Disagreements were resolved through discussion (cf., Akkerman, Admiraal, Brekelmans, & Oost, 2008).

Here follows a short illustration of how the analysis was performed. The extended description of the lessons was interpreted by the first author, these interpretations and conjectures on student learning were checked by the second analyst. This episode shows Lisa performing the first task of the HLT. Our hypothesis on student learning for this task, as formulated in the HLT, is that students solve the task using a light propagation model with a constant speed relative to the lamp or to the graph paper. The analysis therefore focusses on students' actions and utterances that support one of these models (or neither).

The video shows that Lisa places the magnet symbolizing the light flash two squares two the left of the sensor on the picture in the ED at $t = -1$ (See Figure 4.6a). Therefore, the first author conjectured that Lisa reasons with a constant speed of light relative to the graph paper. Lisa then says: *"You would say that it has to be like this, but I think that is strange"* and continues: *"He [the observer] stands here [picture of the ED at $t = 0$] at the fourth square [distance measured from the right lamp], so then he [the magnet/light flash] is here [picture of the ED at $t = -1$] also at the fourth [square measured from the left lamp], so then I would move him [the magnet/light flash] two squares backwards [in the direction of the right lamp] because he [light] moves with two squares per time unit"* (See Figure 4.6b). This last quote and Lisa's actions led the first author to conjecture Lisa reasons with a constant speed of light relative to the lamp.

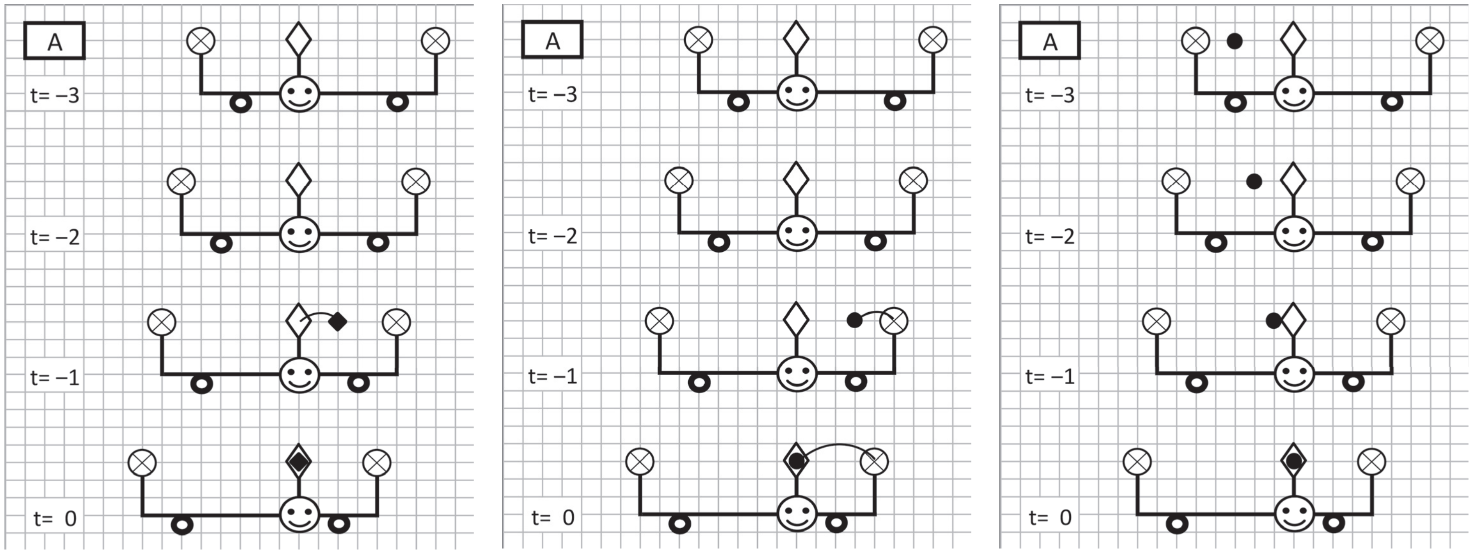

Figure 4.6 Performance of Task 1 by Lisa. Figure 4.6a (on the left) shows the initial positions of the magnet leading us to conjecture she reasoned with a constant speed relative to the graph paper. Figure 4.6b (in the middle) shows the positions of the magnets that led us to conjecture she reasoned with a constant speed relative to the lamp. Figure 4.6c (on the right) shows the positions of the magnets that led us to dismiss our first conjecture and accept the second

This results in two contradicting conjectures about Lisa's pre-instructional light propagation model: A constant speed relative to the graph paper and a constant speed relative to the lamp. The first author then studied the rest of the episode to find out which conjecture is supported by her utterances.

In the teaching experiment, the teacher now took on the role of clinical interviewer and asked Lisa to proceed with the task for the left lamp. Lisa responded*: "I had thought that here [picture* $t = 0$ *of the ED] he [the light flash] has covered 8 squares. So, in the picture before [*$t = -1$ *in the ED] he has covered two [squares] less, light propagates with two squares per time unit, so I figured out that he [the magnet/light flash] would end up at six [squares distance from the left lamp]."* Teacher: *"And before that?"* Lisa: *"At the fourth [square from the left lamp]."* The video shows that Lisa places magnets in the ED at two squares from the left lamp in the picture of $t = -3$ and at the same position as the lamp in the picture of $t = -4$ (Figure 4.6c). This reasoning is consistent with a propagation model constant relative to the lamp. Therefore, the conjecture that Lisa reasoned with a propagation model relative to the graph paper was dismissed and it was concluded that Lisa reasoned with a constant speed relative to the lamp. This interpretation of the lesson and Lisa's reasoning was presented to the second analyst, who checked the conjectures of the first author and agreed with her conclusions. However, throughout the analysis both analysts remained alert to find examples and counterexamples to support or falsify this conclusion.

4.4.2. Results

In this section, we will present the empirical evaluation of the HLT. For each task, we will present what the students did and said while performing the tasks, and our interpretation of this student behaviour with respect to our learning aims. We will also reflect on the learning aims of the three parts of the HLT, and our overall learning aim.

Part 1: Introducing the need for a new light propagation model - Becoming aware of the limited predictive value of pre-instructional light propagation models – Task 1&2

The aim of these tasks is that students become aware of two things: One, (pre-instructional) light propagation models are a constant speed relative to something; and two, there are several options for this something (light source, graph paper). This should make it plausible for students to find out how light propagates.

All students engaged in the first two steps of hypothetical modelling with their initial propagation model: Conform our expectations, they used this model to perform Task 1 and explained the propagation model to the teacher. The students referred to the reference frame of their pre-instructional model by showing how they constructed light propagation in the ED or they mentioned an element in the ED relative to which light had a constant speed:

> ***Daniel*** *(Group B, reasoned with a constant speed relative to the graph paper): Light has a speed relative to the starting point.... final point, actually.*
>
> ***Lisa*** *(Group B, reasoned with a constant speed relative to the lamp): I would say relative to the point where it arrives, …. relative to the cart.*

Daniel referred to the spot on the graph paper where the two light flashes end up at $t = 0$ in the ED. For him, light has a constant speed relative to this point. Lisa counted the speed of light relative to the lamp. Some students also mentioned that the speed of light can be different from different points of view:

> ***Martijn*** *(Group A, about a construction relative to the cart in ED A): Relative to the cart it [the speed of light] is two [squares per time unit], but for the human it is three or one, because of the relative movement.*

When the students dealt with two different propagation models (be it initial or formal), they often described the difference between the two as “taking the movement of the cart into account” or not (for example, see Lisa below). “Taking the movement of the cart into account” refers to light propagation with a constant speed relative to the lamp.

We expected that students might want to choose between two pre-instructional models if both were used to perform Task 1. Martijn is such a student, who considered both models and eventually preferred the paper model over the lamp model:

> ***Martijn*** *(Group A): This [constant speed relative to the graph paper] is more logical. Because it does not matter whether the cart is also moving once light is already moving, because the cart will never catch up with the light. […] and if new light would be emitted that could get further than this light, then it [constant speed relative to the graph paper] would not be correct…but that is not the case.*

Martijn referred to two principles that guide his choice. First, he reasoned that light emitted at one stage cannot be overtaken by light that has been emitted at a later point in time. Secondly, he thought the movement of the lamp should not influence the light flash after it has been emitted. The second principle guided him towards the paper model. Since this model was not contradictory to the first principle, he kept using this model.

As we expected, all students recognized the similarities between their pre-instructional model and one of the formal models and mentioned these similarities.

> ***Daniel** (Group B): My approach is most similar to the wave [...] I only looked at the medium, not at the cart.*
>
> ***Lisa** (Group B): I think that my idea corresponds with the particles, because I take into account that the source moves […] the lamp gives the velocity [to the light particles], or the medium.*

In line with our expectations, all students but one could explain why both formal models are examples of a constant speed relative to something. They also used these models to perform Task 2 and concluded that the two models lead to different task outcomes. Only one student, Kevin, explicitly objected to one of the formal models because he did not recognize that the other model was an example of a constant speed as well. In addition, Kevin had trouble to correctly apply the formal model that did not correspond to his initial model. When fellow student Iris performed the task with the particle-like propagation model, he objected:

> ***Kevin** (Group C): Not convinced. I do not think that light moves that way. The speed of light is constant, also with particles, and now that is not the case.*
>
> ***Iris** (Group C): [Relative] to the cart it is.*
>
> ***Kevin** (Group C): Correct, but I would still look relative to the paper.*

Kevin is very convinced of his initial model and therefore has difficulty to accept that speed can be constant relative to something else than the graph paper. Nevertheless, Kevin was absolutely aware of the difference between the two propagation models. We expected that the models leading to different task outcomes would create some tension between the models that made it plausible for the students to consider different options for light propagation frames. The tension Kevin experienced was not intended in our design.

However, it turned out to be a fruitful moment for Kevin to eventually accept the light postulate.

In the presentation of the wave-like formal model, light speed was defined relative to the “medium” which was represented by the squares of the graph paper in the ED. We expected this to be unproblematic for students. However, Daniel and Lisa were in doubt what element in the ED takes on this role. Instead of the graph paper, as intended, they chose the measuring device (sensor) to have the role of medium. Apparently, the students thought a medium is a kind of object, rather than something light (or sound) propagates through. Since the measuring device and observer are always at the same position in our task design, the students use both these terms.

Lisa applied her version of the wave-like model in ED B, where the measuring device moves relative to the graph paper but is stationary relative to the lamp. This led to confusion because the students expected that the two formal models would give different outcomes, similar to the results they obtained with their pre-instructional models in Task 1. Lisa constructed light propagation with a constant speed relative to the sensor, which led to the same results as a constant speed relative to the lamp:

> ***Lisa*** *(Group B): This is what we had figured out for the wave.*
>
> ***Daniel*** *(Group B): But, isn’t the other one [particle-like propagation model] the same?*

This observation led to a discussion amongst the students how the wave-like propagation model *should* be applied. The students concluded the following:

> ***Lisa*** *(Group B): Each time, you have to take two steps relative to the light…. the observer.*
>
> ***Daniel*** *(Group B): Yes.*

The fruitful position Daniel and Lisa had for finding some tension between the models after preforming Task 1 crumbled because of the confusion they experienced with the wave-like formal model. Their focus shifted from interpreting the outcome of the task to correctly applying the models. As a result, the expected tension between different models predicting different outcomes did not arise for these students, and they erroneously concluded that the wave-like model defines light propagation relative to the observer.

Conform our design, all groups recognized that the two formal models led to different task outcomes. The group of Daniel and Lisa eventually reached this conclusion as well. We expected students would express the need to choose between the models. Except for Martijn, the students did not express this need verbally. However, they agreed with the teacher that it is a plausible step to find out next which of the two models produces correct predictions. Therefore, after performing these two tasks, all students are aware that there is more than one option for the reference frame of light propagation models. As a consequence, the students agreed with the teacher that there is a need to take a further look into these models, but the majority of the students does not actively question the reference frame of the formal models or their pre-instructional model.

Part 1: Introducing the need for a new light propagation model - Becoming aware of the limited predictive value of pre-instructional light propagation models – Task 3

The aim of this task is that students reject both formal propagation models and accept they need to introduce a new propagation model.

All students performed the relative movement task correctly. In line with our expectations, the groups could link the experiments to the corresponding EDs as a result. The students experienced more difficulty with "translating" the outcome of the experiments to light propagation in the ED. Once they were successful with this, supported by the teacher, they could perform this part of the task independently for the second experiment. The following example illustrates how Jeroen summed up the reasoning process of his group:

> ***Jeroen*** *(Group E, about the MME in ED B): Those people [Michelson and Morley] are on earth. Let's imagine that the earth is that cart. They measure the same speed of light, so the two magnets [which the students use to construct light propagation in the ED] should go at the same speed relative to the earth.*

Similar reasoning was observed in the other groups. Subsequently, all groups used the outcomes of the DSE and the MME to evaluate which formal model is confirmed by the experiments and which is rejected. This was also the case for Thomas and Martijn, who proposed an additional third propagation model, a constant speed relative to the observer:

> ***Thomas*** *(Group A, about the MME)**:** For the researcher it [light] moves with two [squares] per time unit, so then he measures the same speed every time.*

Teacher: *Which models do remain now?*

Martijn *(Group A): Keep the observer and the particle.*

For Kevin, interpreting the outcome of the MME turned out to be crucial in accepting that other propagation models than his pre-instructional particle like model are examples of a constant speed, something he struggled with in the previous task. Kevin suggested the particle-like model supports the outcome of the MME; however, he also experienced difficulty with accepting the light propagation mode confirmed by this experiment at the same time:

Kevin *(Group C)**:** This [the particle model in ED B] cannot be correct. The cart has a speed of one square each time. If you then look at the lightspeed, it is three and one.*

Laura *(Group C): But relative to the observer it is just two each time.*

[…]

Kevin *(Group C)**:** It is relativity theory, relative to what… Now [for the MME] we do not look at the graph paper.*

The question "relative to what" in combination with information provided by experiments the experiments helped Kevin to accept the outcome of the experiment, and as a consequence, that other light propagation models are an example of a constant speed as well.

In line with our expectations, all groups obtained the overall task outcome: The MME confirms the particle-like model and rejects the wave-like model in situations like ED B, and the DSE confirms the wave-like model and rejects the particle-like model in situations like ED A. Therefore, all groups performed the third and fourth step of hypothetical modelling: Evaluating the predictions and deciding to accept or reject a model.

We expected that the overall task outcome of the experiment would make it plausible for students to propose a new light propagation model. Two groups agreed with the teacher that a single new propagation model would be more practical than two models with a limited predictive value. In the three other groups, Groups A, C and D, the students showed some form of wondering how to proceed with this conclusion without a prompt from the teacher. For example, Thomas wondered if you can only make predictions with light propagation when you know which model works:

> ***Thomas** (Group A): Should you always find out first whether it [light] is a wave or a particle?*

Iris's (group C) search for a single model that can be applied in all contexts, resulted in that she did not expect the outcome of the DSE. When Laura mentioned that this experiment confirmed the wave-like model, Iris objected:

> ***Iris** (Group C): I do not agree with that. It [light propagation] should be relative to the light source.*
>
> ***Teacher:** Why do you think that it is relative to the light source?*
>
> ***Iris** (Group C): Because we just excluded the wave [with the MME].*

Iris was looking for a single explanation for light propagation: She expected that one of the two models was correct, and that both experiments would confirm this propagation model. She did not consider the option of needing a third model. Therefore, Iris disagreed when this expectation was not met. The teacher discussed with her that, even if they are not what you expect, experimental outcomes cannot be changed. After this discussion, she agreed that the DSE in fact supports the wave-like model:

> ***Iris** (Group C): Then Laura would be right, I think. […] The particle-model is rejected now.*

Eventually, all groups rejected the two formal models and the students found it plausible to look for a new light propagation model.

Part 2: Developing confidence in the light postulate as a propagation model for productive reasoning - Task 4

The goal of this task is that students formulate a new propagation model, the light postulate, and experience this model solves the problem of the limited predictive value of the formal models.

In line with the predicted learning in the HLT, one or more students in each group proposed their own version of the light postulate. The way the students proposed the new model gave the impression this new model was obvious for them. They needed little time to formulate the new model and did not show a need to explain it. This shows the students engaged in the first step of hypothetical modelling with the light postulate. Furthermore, our expectations that it is plausible for students they should find a new propagation model and that the previous task provided them with the necessary tools to propose the light postulate themselves, are confirmed:

***Bart** (Group E): In both cases, it [the light flash] moves two squares relative to the observer.*

***Martijn** (Group A): Relative to the observer, in that case it is always the same.*

***Iris** (Group C): The waves in A and the particles in B? […] in that case it is relative to the observer, two squares, the speed of light. […] Then the speed of light is two squares each time, it does not matter in which situation.*

***Kevin** (Group C): Yes, […] the distance light covers in both situations is the same from the observer's point of view, and it moves the same distance from the observer.*

The students expressed the new propagation model in different ways, but all of them mentioned the constant speed relative to the observer. Note that both Iris and Kevin, who had previously stuck to one of the formal models, now formulate the light postulate themselves.

As intended, the students either checked whether the new model works, or they had mentioned the observer already while interpreting the experimental outcomes in the ED. With these actions, the students verified that the new model confirmed what they knew (the outcome of the experiments) and that it solved the problem of the limited predictive value of the two formal models. In group D, none of the students expressed tension or discomfort with the overall task outcome of Task 3. Nonetheless, one of the students proposed the light postulate:

***Max** (Group D): Could it be that light always moves with the same speed relative to you, the observer. [That] was the case here [points at task A] and also with the previous one, right?*

***Niels** (Group D): This would be in accordance with A wave and B particle, but not with the rest.*

It seems Niels did not recognize that the new model did not need to agree with all the predictions of the previous models. This may explain why the students did not experience tension between the propagation models: They had not recognized that the two models exclude each other.

Part 2: Developing confidence in the light postulate as a propagation model for productive reasoning - Task 5

The aim of this task was that students use the light postulate to make predictions in a new context and use it for a fruitful research programme and discover its consequences for the time of an event.

Conform our expectations, all students but one used the light postulate to perform Task 5. The exception was Max. In his group, Max was the one who had proposed the light postulate during the previous lesson. Now, Max objected that the light postulate would be counterintuitive in the new situation of ED C. He proposed that a constant speed relative to the paper might suit better. The other students in the group corrected him and he agreed that this was not the model they decided upon last lesson. Max used the light postulate in ED D of Task 5.

All students obtained the overall task outcome that the observer of ED C and ED D assign different times to the same event, showing they could use the light postulate to start a fruitful research programme. In line with our expectations, all students expressed this was counterintuitive.

> ***Bart*** *(Group E): Strange that they [the lamps] switch on at different times [for the two observers] while the light[speed] remains the same.*

Nevertheless, 13 of the 15 students committed to the light postulate and showed the expected confidence in the new propagation model. This group includes Kevin, who had great difficulty to consider options other than his pre-instructional model at first. The students therefore engaged in the second step of hypothetical modelling with the light postulate. In each group, at least one student also explicitly engaged in the third step. Conform our expectations, these students described how the task outcome is a consequence of the light postulate and the relative speed between the two observers:

> ***Jeroen*** *(Group E): Because they [the two observers] move at different speeds. [...] Light moves relative to the observer, so if the one observer has a speed relative to the other, it [light propagation] will go in a different way.*

Three students showed some doubt about the validity of the light postulate after performing this task. Two of them reconsidered their initial model as a more suitable alternative:

> ***Martijn** (Group A, about the task outcome): That is not logical, but... […] he [the second observer] will find different values [for time] than the one who is moving. It’s a little strange. [...] [If] the speed of light is the same for all observers, they disagree on the time the light was shot away. [In the next lesson] Or it is not correct that the speed of light is the same for all observers. Those experiments [DSE and MME] showed that it [constant speed relative to all observers] the case, so they [the observers] are both right.*

> ***Daniel** (Group B, about task outcome of ED C): This cannot be correct, because they both cover the same distance to arrive in the middle, so then they [the lamps] should also have turned on at the same time. Maybe we should look at the position of the light where the observer receives it.*

Both students reflected on the counterintuitive task outcomes. Martijn said it was strange that both observers measured different times for the moment the lamp emitted the light flash. He realized that he should either accept this counterintuitive fact or reject the light postulate. The interpretation of the experiments of Task 3 helped him to accept the light postulate. Daniel struggled with the outcome of the first part of the task. He thought that, since the observer is in the middle between the two lamps, he should find that the light flashes were emitted simultaneously. Since this is not the outcome he obtained, he proposed his initial model again. Both these students performed step 4 of hypothetical modelling, although the decision of Daniel to reject the light postulate is not the learning outcome we intended. In conclusion, the tasks in this part resulted in the intended effect that across all participating groups one or more students proposed the light postulate and that all students in our sample used this propagation model to perform the tasks.

Part 2: Developing confidence in the light postulate as a propagation model for productive reasoning - Task 6

The goal of this task is that students reason productively with the light postulate and explore the consequences of the light postulate for time intervals.

All students drew light propagation in ED E. Some of the students struggled with drawing light propagation in ED F: Should the light go vertically upward (and miss the top mirror), or should it move in the horizontal direction as well and hit the top mirror in the middle? These students did not spontaneously use the idea that events that happen in one reference frame, also happen in another frame. Once this issue had been settled, some students thought that the speed of light is the same for both observers in the vertical direction, and the horizontal movement could be ignored. This was an unexpected interpretation of the task outcome. However, in line with our expectations, all students used the light postulate to interpret the graphs of the light path. This way, the students showed they are committed to the light postulate, the fourth step of hypothetical modelling. The students confirmed our predicted learning by concluding that light would need more time to move up and down for the observer studying the moving mirrors:

> ***Kevin*** *(Group B): The light goes different, so they [the observers] do not agree on the time.*
>
> ***Martijn*** *(Group A): [The speed of light] is two squares per time unit, the distance is bigger than twelve [squares], so the time is bigger than six [timesteps].*

The intention of our design was that tension between the two formal models would fuel the need for students to start reasoning with the light postulate and accept this model over their pre-instructional models. We expected this tension to occur in the first part of our design. However, the group of Niels and Max experienced this tension in the third part and used it productively to choose the light postulate as the one and only propagation model. They considered two alternatives: Light either moves faster, or it will take more time:

> ***Niels*** *(Group D): Light goes faster.*
>
> ***Max*** *(Group D): Or it arrives later […] It arrives at a later time, because we had agreed that the speed of light was the same.*
>
> ***Niels*** *(Group D, in a subsequent lesson): For the other observer it is a zigzag pattern. In that case, observer A thinks that the light goes faster, or that it takes a longer time for the light to go up and down.*
>
> ***Teacher:*** *Which of the two is it?*
>
> ***Niels*** *(Group D): It takes a longer time, because light has a constant speed.*

Max initially did not use the light postulate in Task 5. Here, in Task 6, he referred to the light postulate to convince Niels that light needs more time for the observer studying the moving light clock. In a subsequent lesson, Niels used this argument himself to choose the correct but counterintuitive answer. In conclusion, it seems that after performing the six tasks, students in all groups used the light postulate to interpret the light clock thought experiment and accepted the light postulate.

In addition, we expected that students would infer the consequences of a higher relative velocity between the two observers for time dilation. One group (group B) did not infer this by themselves. However, they agreed with the teacher when she talked the group through the reasoning process step by step. The other groups performed this reasoning by themselves. They did so by first describing or drawing the changes of the light path and then interpreting this new path for the duration of the process. Finally, they compared it with the outcome of a slower relative speed.

> ***Teacher:*** *What happens if the relative speed increases?*
>
> ***Thomas and Martijn*** *both draw the light path with a smaller slope and as a consequence longer path: It [the time interval] becomes even longer.*

4.4.3. Contribution of design principles to productive reasoning with the light postulate

Our design was guided by three principles: Students should experience the need for a new light propagation model, that this new model leads to a fruitful research programme and that new knowledge can be developed through hypothetical modelling activities. In this section, we will briefly summarize how the TLS based on these principles contributed to students' learning, thus answering the second sub-research question. This summary is also presented in Table 4.3.

Our teaching and learning sequence consists of two parts, each covering three tasks. The overall aim of the first part is to make the need for a new light propagation model plausible for students. We found that all students engaged in hypothetical modelling with their pre-instructional light propagation models, and that they experienced the limitations of their pre-instructional model. As expected, the students realized the limitations of their models at different points in the task sequence, but in the end, all students agreed that a new light propagation model was needed. However, most students had to be prompted by the teacher to make this insight explicit. All in all, the activities of the first part resulted in the introduction of the light postulate becoming plausible for the students.

The second part of our teaching and learning sequence aims for students to engage in productive reasoning with the light postulate. In Task 4, we found that students in all groups proposed a new propagation model, the light postulate, and in three groups actively compared this new propagation rule to their initial idea. In all groups, one or more students agreed that the light postulate solved the problems the students experienced with their pre-instructional models. The results indicate that the students who experienced a meaningful dissatisfaction with the initial propagation models were more likely to accept the light postulate. In Task 5 and 6, the students derived counterintuitive relativistic phenomena while reasoning productively with the light postulate themselves. Student discourse indicates that during this activity the students came to accept the counterintuitive consequences of the light postulate. Because the students could explain how the counterintuitive task outcome is a consequence of the initial settings of the thought experiment and the light postulate, they feel that the task outcome must be true, although counterintuitive. Almost all (13 out of 15 analysed) students chose to accept the light postulate and continued using this postulate even if it led to counterintuitive outcomes. Furthermore, the students used the light postulate to derive time dilation, engaging in productive reasoning with the light postulate. Thus, the activities in the second part of our design allowed the students to experience that the light postulate solved the problem of the limited predictive value of their pre-instructional models and led to a fruitful research programme. We conclude that, because the students could explain how the counterintuitive task outcome is a consequence of the initial settings of the thought experiment and the light postulate, they feel that the task outcome must be true, although counterintuitive.

Table 4.3 Overview of observed student learning for each task and the frequencies of this learning. Frequencies either refer to the number of students who demonstrated this learning, or to the number of groups in which one or more students demonstrated this learning

Tasks	Student learning	Frequencies
Part 1: Introducing the need for a new light propagation model - Becoming aware of the limited predictive value of pre-instructional light propagation models		
HM with pre-instructional model		
Task 1: Exploring initial ideas	Students engage in the first two steps of hypothetical modelling by performing the task with a pre-instructional model.	All (15) students
	Students explain their pre-instructional model.	14 students
	Students start questioning reference frames for light propagation.	Students in two groups
Task 2: Confronting inconsistencies	Students recognize the similarities between the formal models and their pre-instructional model.	All (15) students
	Students use both formal models to make predictions.	11 students. In one group, the wave-like model was not applied correctly.
	Students accept both formal models.	14 students.
	Students recognize that the two models lead to different task-outcome	

Tasks	Student learning	Frequencies
	Students experience the need to make a choice between the two formal models.	1 student. Students in four groups agree with the teacher when this is proposed.
	Students link the experiments to the corresponding ED.	Students in all groups.
Task 3: Evaluating predictions	Students conclude that one of the formal models is confirmed by one of the experiments and the other is rejected, performing step 3 and 4 of hypothetical modelling.	Students in all groups. Students in all groups.
	Students find it plausible to introduce a new light propagation model.	The students in two groups explicitly, students in the other groups agree with the teacher.
Part 2: Developing confidence in the light postulate as a propagation model for productive reasoning		
HM with light postulate and exploring its consequences		
Task 4: Resolving tension	Students propose their own version of the light postulate, performing step 1 of hypothetical modelling with the light postulate.	Students in all groups.
	Students explain why the light postulate resolves the tension of Task 3.	Students in three groups.
Task 5: Exploring counterintuitive consequences	Students use the light postulate to perform the task, engaging in the second step of hypothetical modelling.	All (15) students.

Tasks	Student learning	Frequencies
	Students express that it is counterintuitive that observers assign different times to the same event.	All (15) students.
	Students explain the task-outcome as a consequence of the light postulate, step 3 of hypothetical modelling.	Students in all groups.
	Students express some confidence in the light postulate.	13 students.
Task 6: Exploring the consequences of the light postulate for time	Students use the light postulate to perform the task.	All (15) students.
	Students use the light postulate to interpret the task-outcome.	Students in all groups.
	Students conclude that the time interval for the observer studying the moving light clock is longer.	Students in all groups.
	Students infer the consequences of relative velocity for the extent time dilation occurs.	Students in four groups.

The development of SRT is operationalized in the design through activities that require students to engage in hypothetical modelling. In these activities, the students explored the consequences of their pre-instructional light propagation model and experienced its limitations. This way, the tasks provided the students with a content-based reason to propose the light postulate. We found that all students could engage in hypothetical modelling, showing that our task design is suitable to inspire this mode of reasoning in secondary students. Relativistic thought experiments require students to reason consistently with the light postulate. Event Diagrams supported the students in stepwise reasoning with light propagation in the context of the thought experiment. As a result, they were able to perform the deductive reasoning to obtain the outcome of the TE themselves. Furthermore, the visualization offered a shared object for the students to express their reasoning and therefore supported discussing their ideas on light propagation, the reasoning process and the overall task outcome.

To sum up, our findings illustrate that the teaching and learning sequence indeed inspired all students to engage in hypothetical modelling and resulted for almost all students in productive reasoning with the light postulate.

4.5. Conclusion and Discussion

Drawing on the Model of Educational Reconstruction (Duit et al., 2012), we proposed a content structure for instruction of SRT. This content structure formed the basis for our design of a teaching and learning sequence that maintained the characteristics of the reasoning process of SRT to introduce relativistic concepts. This TLS was presented in the form of a hypothetical learning trajectory with hypotheses about the learning process to be seen. Finally, this HLT was evaluated in a teaching experiment with small groups of students. In Section 4.2.4 and 4.4.3 we have answered our two sub-research questions. Here, we return to our main research question:

> *How can learners in secondary education develop a conceptual understanding of SRT through engaging in a process of physics theory development?*

The students participating in our study developed a conceptual understanding of SRT. Thirteen out of 15 students developed confidence in the light postulate as a propagation model for productive reasoning. They used the light postulate to derive other relativistic concepts and, in this process, interpreted velocity, the time of an event and duration relative to a specific reference frame. In the lessons, the students engaged in hypothetical modelling activities with their pre-instructional light propagation model and the light postulate. Einstein also drew on this style of scientific reasoning when he introduced SRT in his article *Zur Elektrodynamik bewegter Körper*. Furthermore, the process of theory development was reconstructed for students by carefully designing the tasks so students could experience a mismatch between two theoretical ideas. Introducing SRT through this process of theory development starting from a meaningful dissatisfaction with their pre-instructional ideas was a fruitful approach to introduce SRT to secondary students. Therefore, we have proposed a successful approach to achieve productive reasoning with the light postulate and let students experience that the concepts of SRT are interconnected. However, the learning process that led to these learning outcomes varied between the students, as a short summary of the learning process of Martijn and Kevin illustrates.

Martijn proposed three different light propagation models while working with the initial task. This way, he created friction between theoretical ideas by himself. The tasks helped him to dismiss two of these initial models on content-based reasons and to choose the light postulate as final light propagation model. He then used the light postulate to derive the relativity of simultaneity and time dilation and reasoned with the consequences of higher relative velocities on the phenomenon of time dilation.

Kevin showed a strong preference for his pre-instructional light propagation model. He did not accept that a different propagation model was also an example of constant speed, just a constant speed relative to something else. Kevin therefore did not realize at the expected moment that there were more options for constant propagation. However, he did come to this realization in a different task. The outcome of the experiments helped him to realize that there were more possibilities for a reference frame of constant propagation than just his preferred frame. He later used the overall outcomes of the two experiments to formulate the light postulate himself. Although the consequences of the postulate were still counterintuitive to Kevin, he kept using this new propagation model in subsequent tasks and he used the light postulate to derive time dilation in the light clock thought experiment.

Bakker (2018) mentions that HLTs are sometimes seen as rigid and as forcing students and teachers to follow one strict learning path. Although this criticism is not shared by early implementers of HLTs (Bakker, 2018; Simon, 1995), we paid special attention to avoiding this unwanted feature of HLT in our design. Specifically, we designed the tasks in such a way that students could come to the realization of the limitations of their pre-instructional model while working with different tasks, without stopping the flow of the lesson series. The learning paths of Martijn and Kevin illustrate that the design did allow for such differences in student learning. These learning paths also show that the students did try to develop a consistent physics understanding of the world, and that carefully designed tasks can help these students to bridge the gap between their pre-instructional ideas and physics concepts.

One of our learning aims was to engage students in hypothetical modelling. Although our task design was successful in supporting the students to attain this learning goal, we also acknowledge it is possible to improve our task design even further to support students in this endeavour. First, some students experienced difficulty with reflecting on the overall task outcome because they were unsure about their reasoning with one of the light propagation models. We therefore propose to make a clear distinction between these two reflective activities. Before reflecting on the overall task outcome, students and teacher need to check if they reasoned consistently with the light propagation model at hand.

Second, the students engaged in hypothetical modelling activities, but we did not make this explicit to them. If we want students to become aware of Nature of Science-aspects in science education, there should be explicit attention not only on what they have learned, but also on how they (and scientists) reason (Lederman, 1992). Furthermore, this awareness may also contribute to overcome two difficulties some students faced while working with our tasks. Some students experienced difficulty to reason with one of the formal models. Underlining hypothetical aspect may help these students to overcome their initial hesitation: They are not required to be committed to the model, and may later reject it. The students are only asked to explore what the task outcome would be, were the model to be correct.

In the second task, all students recognized that the outcomes of both models are different. However, not all students realized that, as a consequence, the two models cannot be true at the same time. This issue may also benefit from underlining the hypothetical aspect of the models: Both models are plausible, and we temporarily assume them to be true. Subsequently, we can support students with the interpretation of this hypothetical aspect: Although both models can be true, they cannot both be true at the same time.

A well-known problem with learning relativity is that students do not distinguish between the occurrence and the observation of the event (Scherr et al., 2001). We did not encounter this learning problem with our students. Our task design may have contributed to avoiding this misconception. In the first tasks, students would be presented with the observation of an event and they had to figure out when the event occurred in a specific reference frame. In the final task, students worked with an intelligent observer who compensated for signal travel time. The tasks confronted students with the difference between the occurrence and the observation of an event. It would be interesting to explore if students keep making this distinction when it is not stressed by the task design.

We used thought experiments supported with Event Diagrams to bring the relativistic world to students. We used the thought experiment in a specific task design: Students were free to choose the model with which they wanted to execute the thought experiment and students had to perform the deductive reasoning to obtain the outcome of the experiment themselves. However, one could argue that to truly perform a thought experiment, the student has to be free to pose the central question of the TE and to choose the basic settings of the TE as well. It may be clear that such an open application of TEs did not suit our learning aims. However, this means that we have given an example of how to use thought experiments to introduce relativistic concepts, and that it would be interesting to further explore how students could benefit from an open TE.

The design choice to visualize the TEs with Event Diagrams is a central feature in our teaching and learning sequence. It was important for our design that students would engage in the deductive reasoning with light propagation of the thought experiments themselves. The ED allowed students to do that by supporting step-wise reasoning with light propagation. For instance, computer simulations have been widely used to visualize relativistic contexts (Carr & Bossomaier, 2011; De Hosson, Isabelle, Clémént, Etienne, Tony, & Jean-Marc, 2010; Savage, Searle, & McCalman, 2007; Sherin, Tan, Fairweather, & Kortemeyer, 2017). Because the reasoning with light propagation in these visualizations is often embedded in the algorithm, these types of visualizations do not support students in the deductive reasoning with light propagation. However, these visualizations allow students to tweak the initial settings of a thought experiment and explore the consequences of these basic settings on the outcome of the TE. We briefly explored this in Task 6. Therefore, a combination of visualizations may be beneficial for students to learn SRT.

We structured our design process with the Model of Educational Reconstruction. The model allowed and stimulated us to regard learning consequently in the coherence of theory, student learning difficulties and learning aim. The model stresses the importance of reconstruction of the science content for education and as such provides certain liberties to not strictly follow the historical logic of theory development, but to draw on these ideas to make a didactical structure that makes sense from the perspective of a novice learner. Two tasks in our design reflect this aspect of MER. First, the use of the analogy between students' pre-instructional models and two historical models to inspire consistent reasoning whilst still keeping the connection with students' ideas. Second, the use of the outcome of the De Sitter Experiment and the Michelson-Morley Experiment (MME) to allow students to evaluate their predictions with these previously mentioned historical models. The MME has a different role in the history of physics, but we drew on its outcome in our didactical reconstruction to allow students to make sense of the outcome in a context they could understand.

It has been suggested that the concept of event plays a crucial role in student learning to *"redefine space and time according to the new constraints of the theory, that is the unsurpassable and constant speed of light"* (Levrini, 2014, p. 162). As we have shown in our theory analysis and what also follows from this quote, relativistic reasoning draws both on the concept of event and of absolute light propagation. For this introduction to SRT, we focussed on the light postulate, because it is a central theme in the Dutch curriculum goals for SRT. However, we do not wish to contradict the importance of the concept of event. Our intervention may even form a starting point to introduce the concept of event on content-based reasons from a student perspective, since the students now have experienced that the time and place of events do not have the same values for all inertial observers.

The Model of Educational Reconstruction furthermore underlines the importance of iterative design cycles to test and refine the educational design in the educational practice. To this end, Komorek & Duit (2004) suggest evaluating the design using a Teaching Experiment, working with small groups of students to find out learning patterns of students. In addition, we think it should always be an aim of designers and researchers of education to embed the design into real life praxis. To make such larger scale evaluations useful, a sound basis of knowledge of possible learning paths of students is needed (Lijnse, 2001). With this research, we have provided the first, and crucial, step towards classroom evaluations. However, the current version of our design cannot be directly implemented in the classroom as it relies heavily on a teacher working closely with students individually to guide their reasoning. A subsequent design should address this issue to allow students to work more independently with the tasks, while keeping the feature that students can explore and challenge their ideas. In this version of the design, we have shown that students can follow different learning paths to obtain the learning goal, this should be retained in a new design. Finally, the students we worked with were highly motivated to participate in the study. One could imagine that working with a classroom of students who did not volunteer to study relativity will face the teacher with some motivational issues as well (Bøe, Henriksen, & Angell, 2018). We propose that the minds-on approach of our tasks may address these motivational issues and engage students in their learning process.

In conclusion, we have shown that a teaching sequence based on hypothetical modelling with students' pre-instructional light propagation models engages students in the process of theory development of SRT and results in students gaining a conceptual understanding of SRT. This study provided a detailed account of possible student learning when working with the educational design, thus providing a proof of principle. We expect this approach can also be fruitful in the classroom when the earlier mentioned concerns are addressed and improvements implemented to make the design suitable for larger groups. We intend to implement these adaptations and see if these results can be reproduced in the classroom in our next study.

Chapter 5

Introducing the Light Postulate in the Secondary Classroom

Abstract – It is desirable that secondary students are introduced to Special Relativity Theory, one of the iconic theories in physics. However, gaining an understanding of relativistic concepts has proven to be difficult. The evaluation of teaching approaches addressing this issue is usually done with small groups, ignoring the specific challenges of the classroom context. We present the adaptation for the classroom of a Teaching and Learning Sequence (TLS) introducing the light postulate to 11th grade pre-university level secondary students. Evaluation of this classroom TLS with seven classes shows that the majority of the students can use the light postulate to perform relativistic thought experiments.

Key words – Special Relativity Theory, Secondary Education, Teaching and Learning Sequence, Classroom, Professional Learning Community

5.1. Introduction

Special Relativity Theory (SRT) is an iconic theory that represents a major theoretical shift in how physicists look at the world. It is desirable that secondary students also encounter these important ideas as part of their education in physics. The fact that SRT has been introduced in many secondary physics curricula over the past years, illustrates this notion. However, SRT concepts are difficult to learn for students on all levels of education (Gousopoulos, Kapotis, & Kalkanis, 2016; Guisasola, Solbes, Barragues, Morentin, & Moreno, 2009; Pietrocola & Zylbersztajn, 1999; Scherr, Shaffer, & Vokos, 2001; Scherr, Shaffer, & Vokos, 2002; Selçuk, 2010; Villani & Pacca, 1987). SRT changes concepts such as time, duration, place, length, mass, and energy. Instead of seeing these as absolute concepts or intrinsic properties of an object, these notions can be viewed only relative to a reference frame. Phenomena such as velocity, (the relativity of) simultaneity, time dilation and length contraction become apparent when two reference frames are compared. Relativistic phenomena only differ from their classical counterparts when the speed between reference frames is high, much higher than speeds we encounter in daily life.

To gain a conceptual understanding of these counterintuitive phenomena, teaching approaches need to bridge the gap between students' pre-instructional ideas and the relativistic concepts. The number of studies addressing these issues for secondary students are limited. Velentzas and Halkia (2013) proposed that thought experiments can be helpful tools to introduce relativistic concepts to secondary students, and the study by Kamphorst, Vollebregt, Savelsbergh and van Joolingen (2021b) presents a local theory on what student learning can look like when introducing the light postulate through a meaningful mismatch between pre-instructional light propagation models. Both these approaches were tested in small scale settings only. Although the studies show promising results and ideas, there is a need for evaluation in realistic classrooms.

Both approaches lean heavily on discussion in small groups of students. Involving students in such a discussion requires a different approach in the context of a classroom with 20 to 30 students compared to small groups. This may also hold for the way tasks are introduced to students and how the theoretical yield of performing these tasks is explicated to and shared with students. In addition, the approaches, and the extent to which the teacher can anticipate and react to students' difficulties is also dependent on context. All in all, approaches that have proven to be successful in small scale settings, may not be successful when they are implemented as is into the classroom. Instead, they should be redesigned with the classroom context in mind.

To proof the value for education, interventions should not only be evaluated in ideal laboratory settings, but also in realistic classrooms. The aim of this study is to address this issue by redesigning the approach described by Kamphorst et al. (2021b) for the classroom setting and evaluate the resulting classroom intervention. To this end, we draw on insights from design research, involving teachers in an iterative design process. The resulting TLS will be evaluated in the classroom setting and compared to regular approaches. We therefore have the following research questions:

1. *How can the small group TLS be adapted for the classroom context?*
2. *To what extent is the intended learning achieved with the classroom TLS?*
3. *How do learning outcomes with the classroom TLS compare to those of regular teaching approaches?*

First, we will briefly present the small-group TLS and local theory on student learning. Subsequently, we will address the used methods to redesign and evaluate the small-group TLS for the classroom. After that, we will present the results of the redesign and evaluation. We will conclude with answering our research questions and discussing some limitations and implementations of this study.

5.2. Small group implementation of the TLS and local theory on student learning

In a previous study, we have conducted an educational reconstruction of SRT, designing and evaluating a small-group teaching and learning sequence (TLS) that takes student's ideas as a starting point to introduce relativistic concepts (Kamphorst et al., 2021b). In this reconstruction we have identified the light postulate as the central concept of SRT. This postulate states that the speed of light is finite and the same for all inertial observers and is used in deductive reasoning processes to derive other relativistic concepts. Thus, forming a connecting element in the theory. Therefore, the main learning aim of the TLS is that students can use the light postulate in productive reasoning. This means that students know the light postulate, and that they can use it in relativistic contexts to derive relativistic concepts such as the relativity of simultaneity and time dilation. To reach this learning aim, the design intends that students experience:

1. A need for a new light propagation model, i.e. the light postulate, and that this need is plausible from their perspective,
2. That the light postulate solves the problem introduced by the need for a new propagation model and this new model leads to a fruitful research programme, and
3. The process of theory development of SRT through hypothetical modelling.

These three features were implemented in the TLS by designing 6 tasks that engage students in two cycles of hypothetical modelling, first with their pre-instructional light propagation model, subsequently with the light postulate. Task 1-3 introduce a mismatch between two light propagation models through hypothetical modelling with students' pre-instructional light propagation models. Task 4-6 allow students to solve the mismatch through hypothetical modelling with the light postulate. While performing these tasks, students also explore the consequences of the light postulate and derive relativistic phenomena such as the relativity of simultaneity and time dilation. The tasks engage students in hypothetical modelling activities through reasoning tasks in which students perform a thought experiment (TE).

Hypothetical modelling consists of four steps: (1) proposing a model, (2) using the model to make predictions (3) reflecting on the reasoning process, and (4) deciding to accept or reject the model. These steps partly overlap with the three phases of a thought experiment: (1) describing the initial situation, theory, and central question of the TE; (2) performing the TE through deductive reasoning and obtaining an outcome, thus answering the central question; (3) reflection on the outcome and drawing an overall conclusion. Proposing a model is a part of defining the theory to use in performing the TE; using the model to make predictions is part of the deductive reasoning process to obtain the outcome of the TE and deciding to accept or reject the model is a part of drawing the overall conclusion of the TE supported with a graphical representation of spacetime, the Event Diagram (Kamphorst, Savelsbergh, Vollebregt, & van Joolingen, 2021a).

In the evaluation of this approach with small groups of students, we showed that the TLS results in productive reasoning with the light postulate: The students developed confidence in the light postulate and used this new model to derive and interpret relativistic phenomena such as the relativity of simultaneity and time dilation.

5.3. Method

The research questions are answered in two parts. The first research question will be addressed in the design study. The second and third research question will be addressed in the evaluative study. We will discuss the method for these two parts separately.

5.3.1. Design study

To answer our research questions, we adapted the small-group TLS into a TLS for the classroom in close collaboration with a group of physics teachers. The teacher collaboration was organized in the form of a professional learning community (PLC), that ran over a course of two years.

Participants

In the first year, ten teachers of six different schools participated in the PLC. There were five 4-hour meetings. In the second year, eight teachers of seven different schools participated in all sessions of the PLC. This series consisted of ten 4-hour meetings. One teacher quit the PLC after the first year. All teachers who were the only ones from their school to participate, could invite a colleague to join in the second year. During the second year, two teachers quit the PLC. One for health reasons, and one stopped showing up and responding to communications. In both years, the first author participated as chair of the PLC and a former teacher trainer assisted in preparation, reflection, and small group discussions with the participants.

Professional Learning Community

The close collaboration with teachers in the PLC had a threefold aim. The first aim was to ensure classroom feasibility of the design. Teachers are experts in guiding and shaping learning processes in the classroom context. We draw on this expertise to adapt the small-group TLS for this new context. The second aim was to create a sense of ownership with the teachers. We expected that ownership of the classroom design motivates teachers to put in the extra effort of participating in the study and contributes to executing the design in the classroom with a shared interpretation of how this should be done. It is reported in literature that design studies often go wrong on this aspect (Binkhorst, 2017; Brown & Campione, 1996; Ormel, Roblin, McKenney, Voogt, & Pieters, 2012; Tabak, 2004; Voogt, Pieters, & Handelzalts, 2016). The third aim was to educate teachers to teach SRT. Since the subject is new in the curriculum teachers have little knowledge on what difficulties students may encounter while learning new relativistic concepts, and how to deal with these difficulties to help students overcome them.

Each year of the PLC formed a design cycle to adapt the TLS for the classroom. The focus of the first design cycle was to adapt the tasks of the small-group TLS for the classroom. Teachers worked in duos and each team designed a lesson focussing on one of five relativistic concepts: Relativity postulate, pre-instructional light propagation models, light postulate, time dilation and length contraction. These lessons were based on tasks of the small-group TLS. The result of this design approach was that the teachers were familiar with the lesson they designed themselves, but less familiar with the work of colleagues. Implementing the lessons rendered three major points of improvement: Teachers did not experience a coherence between the lessons, something that was present in the small-group TLS, an introductory lesson in performing a (supported) TE in a classical context was deemed necessary and extra attention on how to perform a TE in the setting of a classroom was needed.

The focus of the second design cycle was to address these issues. In constructive group discussions, the teachers and first author discussed what issues the teachers faced with the teaching material, and how the material may be adapted to overcome these issues. The improved teaching activities were performed in the PLC meetings to ensure that all teachers are familiar with the material, create a shared understanding of the aims of the materials and how teachers can respond to expected student difficulties. This is also reflected in the explicit description of the teacher’s role in the classroom TLS.

5.3.2. Evaluation study

To answer the second and third research question, the TLS was evaluated in the classroom context and student learning was compared to that of students taught with regular approaches.

Participants

A total of 12 teachers, teaching 17 classes in nine schools participated in the evaluative study of the final version of the classroom TLS. All students were enrolled in the 11th grade of pre-university level secondary school. Four teachers, teaching seven classes with a total of 188 students altogether, used the materials designed in the PLC. Eight teachers teaching ten classes with a total of 201 students used a regular approach.

The teachers of the intervention group, without exception, described their classes as not cooperative. This contrasted from their experiences with teaching the intervention in the previous school year. The teachers of Class 1 and 4, Tjitske and Bas, described their classes as “more difficult than last year” (Tjitske and Bas), whereas the teachers of the other classes, Nienke and Judith, described their students attitude as “done with the school year” (Nienke, classes 2 and 3), and “actively sabotaging exercises because they did not feel like participating” (Judith, classes 5-7). Bas described that his students did go through the motions of the exercises but were waiting for their teacher to tell them the answers. Teachers in the control group faced difficulties with their classes too, but not to this extent. An explanation may be that the intervention group taught SRT later in the school year, closer to the summer holidays (May – July) than the control group (January-April). This shift in time was not intentional. However, it may have impacted the students’ learning attitude, which often decreases at the end of the school year.

Inclusion criteria

In classes who were included in the study, six to twelve lessons were spent on relativity. These lessons covered at least the subjects of relative movement, reference frame, light propagation, relativity of simultaneity and time dilation. This corresponds to the six tasks of the TLS. Of the eight teachers that participated in all the PLC sessions of the second year, one had not taken part in the first design round and was therefore excluded from participating in the study. Three other teachers did not perform the TLS up to this point in their classes. The results of these teachers are therefore excluded from the analysis.

Datacollection and instruments

The second research question is answered by probing student learning outcomes with the TLS through collecting five tasks and analysing how students perform a TE in the posttest. In addition, semi-structured interviews with the teachers of the intervention group were conducted. The third research question is answered by comparing students’ learning outcomes to that of students taught with regular approaches with a pre- and posttest. The pre- and posttest consisted of items of the relativity concept inventory (RCI). Additionally, in the posttest students were given two computational items and two reasoning items in which they perform a TE. The pre- and posttest were administered to the intervention group and the control group.

Hand-in Tasks of TLS

The classroom TLS has two main learning aims: Introducing a need for a new light propagation model and productive reasoning with the light postulate. Whether or not the TLS succeeded in these aims was checked by collecting five tasks. These tasks probe if students:

- Reason with a consistent pre-instructional light propagation model;
- Think the two formal light propagation models are plausible and exclude each other;
- Propose the light postulate;
- Apply the light postulate in the context of a familiar TE;
- Interpret the outcome of the light clock TE in line with the light postulate.

The tasks are part of the TLS and can therefore not be used as measuring instruments with a different approach. However, they provide a valuable insight in student learning. Students perform the tasks individually, and the tasks are handed in directly after students performed them. The tasks are coded with being in line with our expectations as formulated above, or not. An overview of the hand-in tasks and how they were coded is given in Appendices A and B.

We used the TE of our pre-instructional reasoning study (Kamphorst, Vollebregt, Savelsbergh, & van Joolingen, 2019) as a basis for the first task. This is a change compared to the small-group TLS, although the aim is not changed. The reason for this adaptation, is that we thought this TE is more suitable to perform individually with little instruction, whereas the TE in the small-group approach was quite complicated to perform without teacher guidance. In addition, the outcome of the first task can now be compared to our findings in the pre-instructional reasoning study.

Teacher interviews

The teacher interview was structured with three vignettes. Each vignette described a fictive task, comparable to tasks in either the TLS or regular approaches, and the discourse of two students discussing the task. This student discourse was based on data obtained at the evaluation of the small-group TLS. The first vignette described students discussing light propagation from a moving light source, using pre-instructional models; the second vignette described a computational task on time dilation in which students are focussed on identifying the reference frame for proper time; the third vignette describes the light clock thought experiment and students interpreting the longer light path, discussing whether to use the light postulate or a pre-instructional model.

The vignettes were presented to the teachers, and they were asked if they recognized the task and the student discourse from their own practice. Subsequently they were asked to illustrate this with an example from their own practice. The interview was conducted with all participating teachers via telephone and audio recorded. Teachers received the vignettes beforehand through email with the instruction not to look at them before the interview. The responses of the intervention group teachers are used to illustrate the results.

Relativity Concept Inventory

Students' conceptual understanding was probed with the Relativity Concept Inventory (RCI). The RCI (Aslanides & Savage, 2013) is a validated test that aims to assess students conceptual understanding of relativistic concepts with conceptual multiple-choice items. The number of answer options per item range from two to four. Items on length contraction, the mass-energy equivalence, velocity addition and causality were excluded from our tests, because these concepts were not part of the minimum concepts to cover for participating in this study.

The results of the RCI indicate that this test is not suitable to probe conceptual understanding of relativity with our sample. 314 students took the RCI at a pre- and posttest. The mean normalized gain was close to zero (-0.05). Furthermore, the KR20 reliability, a measure for the internal consistency of the RCI, has a negative value (-0.34) for our sample. This means that that the items do not measure an underlying concept for our sample. Finally, the mean item difficulty in the posttest, defined as the ratio between the number of correct answers and the total number of answers given, is with a value of 0.46 close to the percentage of correct answers we would expect if students guessed their answers: 0.37. Therefore, we will not use this tool to evaluate student learning. We will take a closer look at the reasons why the RCI is not a suitable instrument to measure SRT learning for our population in the discussion section.

Reasoning items

The reasoning items describe an initial situation and students are asked to explain how the situation develops further, thus performing a TE. In these items, two observers, one on a platform and one on the train, watch a lamp in the middle of a train wagon emitting a light flash in all directions. The first item asked students to explain whether the light flashes hit the sides of the train simultaneously, thus deriving the relativity of simultaneity. The second item asked students to explain if the light flashes return to the middle of the train simultaneously, probing either reasoning with the light postulate or applying the relativity postulate.

The items were scored by assigning points for explaining the situation correctly for both observers and arriving to the correct conclusion. The total score could range between zero and five points. Additionally, the first reasoning item was coded with three extra parameters: The number of correct answering elements students used, the number of reference frames they referred to and finally, if their reasoning was in line with the light postulate. These variables are not independent. Students can only answer in line with the light postulate when they refer to two reference frames and their answer contains at least 4 correct elements.

Computational items

The two computational items are on time dilation. A relativistic situation is described and the time interval for one observer is given. Students are asked to compute the time interval for the other observer. The items were scored by addressing points for using the correct equation, identifying the reference frame for proper time and producing the correct answer. The total score ranged between zero and six points. An additional code was assigned to distinguish between students blindly entering numbers in equations and students who can apply the equations correctly to relativistic contexts. This code identifies if students identified the rest frame correctly for both questions.

5.4. Results

In this section, we will address the three research questions separately. First, we will present how the small-group TLS was made feasible for use in the classroom. In the next section we will present some data that illustrate students' learning when being taught with the classroom TLS. In the third section, we will compare students' learning in two conditions: When taught with the TLS and with regular approaches.

5.4.1. Adapting the Teaching and Learning Sequence for the classroom

Here, we will describe the adaptations made to the small-group TLS[1] in adapting it for the classroom. This process focussed on three aspects:

1. Executing a TE in the classroom;
2. A coherent lesson series; and
3. Introducing the overall approaches of a supported TE in a non-relativistic setting.

The TLS can also benefit from a setting with more students: The chance that all pre-instructional models are mentioned by the students themselves is more likely when working with a large group, resulting in a mismatch that is not created artificially by the teacher.

In all tasks of the TLS students perform a TE. In the small-group design, the reasoning task and central question were introduced by the teacher. Students subsequently performed the deductive reasoning to obtain a task outcome. The reflection on reasoning process, task-outcome and drawing of an overall conclusion were part of the ongoing dialogue between teacher and students as well. In the classroom setting it is not possible to maintain an ongoing dialogue between the teacher and all students. As a result, we expect many students not to engage in performing the TEs themselves if the same approach is used in the classroom setting. Therefore, the lessons are structured in four phases that support the steps of hypothetical modelling and performing TEs for all students.

In the first phase of each lesson, the teacher introduces a central question. In the second phase, a reasoning activity is introduced that allows students to answer this central question. As part of the activity, students propose a model (often implicitly by using it in solving the task). Students use this model to perform the reasoning task and obtaining a task outcome. By doing so, they make predictions with the model. The final part of the reasoning activity is to reflect on the reasoning process by correcting the task using a correction sheet. In phase 3, students perform a task in which they reflect on the outcome of the thought experiment. In a classroom discussion, students exchange their reflection outcomes, the teacher guides this discussion to the conclusion of the thought experiment in answer to the learning question. The fourth and final phase of the lesson serves as a reflection on the lesson as a whole: The teacher

[1] The teaching materials are published at www.fisme.science.uu.nl/toepassingen/28984/

summarizes the activities in the lesson and consolidates the answer to the central question. This way, all steps of performing a TE are addressed in separate lesson activities, giving all students the chance to explore and communicate their ideas.

The tasks in the small-group TLS form a strong and coherent unit. This coherence was lost in the first design round of the classroom TLS. The teacher teams designed individual lessons introducing one relativistic concept. They did not pay attention to their lesson being a logical continuation of the prior lessons. Teachers experienced this as problematic. For the final design evaluated in this study, special attention was paid to reintroduce this coherence between the subsequent tasks and lessons. The clear lesson structure was supportive for this endeavour. First, this structure supported the internal coherence of each lesson. In addition, the teachers discussed how the answer to a central question given in phase four, can raise a new question that can be addressed in the subsequent lesson. This ensured that there were no “gaps” between lessons: Tasks that refer to concepts or skills that students did not have the chance to learn. Teachers also mention this in the reflection on executing the two versions of the classroom TLS. Nienke: “*It did go more smoothly, because it was more of a whole.*” Tjitske: “*Last year [version 1] it was less coherent. That time, students learned stuff by heart. This time [version 2] it made more sense to students.*”

In the small-group version, the graphical representation supporting the TEs is introduced in the first relativistic task. Students can work well with this representation, but they need some training to learning how to perform TEs with this instrument. Teachers expected that in the classroom setting, learning how to perform a supported a TE may prevent students from becoming aware of their pre-instructional light propagation model. Therefore, students learn to work with the graphical representation supporting the TEs by performing a thought experiment on relative movement in a classical context in an introductory lesson. In addition, some concepts that are useful for the lesson series were introduced in this lesson: The concept of event as a happening that has a specific time and place, and the idea that events happen in all reference frames.

In addition, we made three smaller adaptations in the design. The first adaptation is to provide a written source for theory. In the small-group setting the teacher would repeat the theory if a student forgot something. In the classroom setting, students are sometimes absent or do not pay proper attention and therefore need a source to look up the information they missed.

However, this need is at odds with the aim of the lesson series to allow students to explore their ideas. A compromise was found in providing this information at the end of each lesson instead of handing out a textbook with all theory at the beginning of the lesson series.

The second adaptation is in the name we give to students' pre-instructional light propagation models. Both in the small-group evaluation and experiences of teachers with the first version of the classroom TLS it was observed that referring to the two formal models (and corresponding student models) with the words "particle-like" and "wave-like" model caused confusion for some students (Kamphorst et al., 2021b). In evaluating the models, these students did not focus on what they knew on the outcome of the TEs and the speed of light. Rather, they started wondering whether light is a particle or a wave ("Thomas: *Should you always find out first whether it* [light] *is a wave or a particle?*" (Kamphorst et al., 2021b, p. 29)). This query obscures the transition to thinking in terms of a new light propagation model. We therefore introduced a term that is more open for changing the light propagation models it in the future. This was found in referring to students' pre-instructional light propagation models as a "propagation rule." Students are asked what rule they used to draw light propagation in the first tasks.

Thirdly, the TLS is concluded with a final lesson in which the equation for time dilation is derived from the light clock thought experiment by students themselves. This lesson was also part of the small-group TLS, but not part of the evaluative study, because that focussed on the introduction of the light postulate.

5.4.2. A closer look: Learning process and outcome with Teaching and Learning Sequence

In this section we describe the learning process and outcome of 62 students who were taught with the classroom TLS. To that end we discuss student answers to the 5 hand-in tasks and one of the reasoning items in the posttest. Together, these tasks give an overall view of the learning process that contributed to the three learning aims of our educational design: (1) introducing the need of a new light propagation model (Task 1-3); (2) productive reasoning with the light postulate (Task 4-6); and (3) allowing students to engage in the process of theory development through hypothetical modelling (Task 1-6). We will give a short description of the participating classes before continuing to students' learning process and outcome. For each learning aim we will discuss students' answers to the tasks contributing to this aim and thus evaluate to which extent the aim is met. This evaluation of the students' learning process is illustrated with the teachers' reflection on the classroom discussions. This section is concluded by discussion the reasoning item on the posttest for this sample, placing it in context of the learning process with the TLS, and describing students individual learning paths. The results are summarized in Table 5.2 and Figure 5.1.

For the purpose of creating as complete an image as possible of what student learning with the classroom TLS look like, the analysis presented in this section will focus solely on the students who handed in all tasks. This are 62 of the 209 students of the intervention group, 56 of them also took the posttest. A complete overview of the number of students per class is given in Table 5.1. It is worth noting that the fraction of students who attended all lessons varies widely over classes. In Classes 1 and 2, half of the students handed in all tasks, whereas in Classes 3, 4, 6 and 7, this is only one third. In Class 5 even fewer students handed in all tasks.

Our first learning aim is that the design should enable students to experience the need for a new light propagation model. Almost all students use a consistent pre-instructional light propagation model (Task 1, Figure 5.1). In the individual reflection on Task 2, most students acknowledge that both consistent propagation models are plausible models for light propagation (Reflection 2a, Figure 5.1). Only a small fraction of them also recognizes that these models, although plausible, cannot be true at the same time (Reflection 2b, Figure 5.1). These results show that the students have the building blocks for a meaningful mismatch between the two propagation models (and for the need for a new propagation model), but that they do not recognize this themselves. However, the mismatch between the two propagation models is also addressed in the subsequent classroom discussion.

Table 5.1 The number of students that completed all 5 hand-in assignments for the total number of students in the class

	Total	1 (Tjitske)	2 (Nienke)	3 (Nienke)	4 (Bas)	5 (Judith)	6 (Judith)	7 (Judith)
Handed in all tasks	64	13	15	9	8	4	7	8
N	209	24	27	29	28	27	25	26

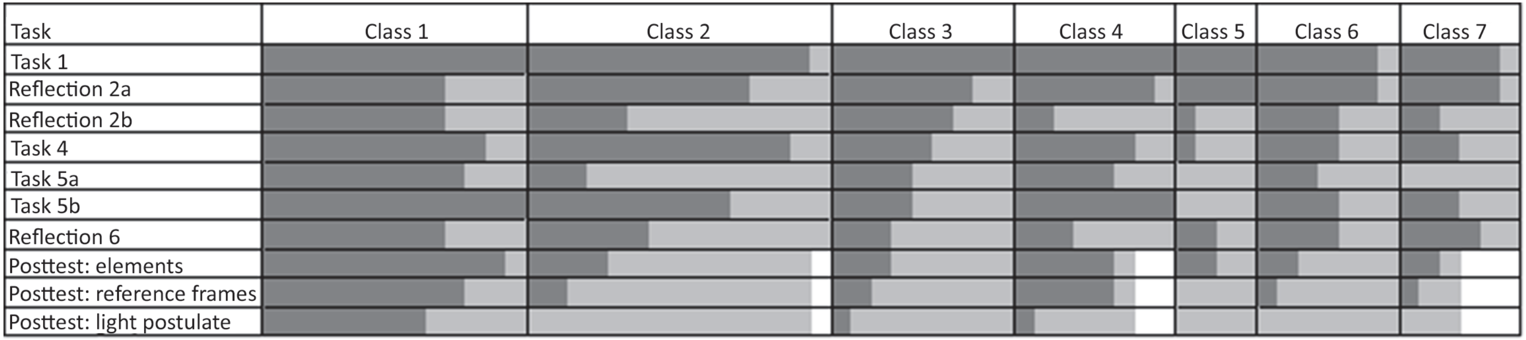

Figure 5.1 Visualization of student responses to the hand-in tasks. The dark bars represent responses in line with our expectations, the light bars represent answers not in line with our expectations. The white bars represent missing responses. Not all students who handed in all five tasks also performed the post-test

The second learning aim is that the design should enable students to experience that the light postulate solves the problem introduced by the need for a new propagation model and this new model leads to a fruitful research programme. For most tasks a vast majority of the students answered in line with our expectations (Figure 5.1). These students proposed the light postulate (Task 4a) and applied it in a thought experiment deriving the relativity of simultaneity (Task 5b). These results show that many (two thirds) students propose the light postulate, solving the mismatch between the two formal propagation models. In this light, it is remarkable, that the fraction of students who give a correct definition of the light postulate is so much lower (Task 5a). Also, students who gave an incorrect definition used the light postulate to interpret the light clock thought experiment (Reflection 6a).

The third aim was that students would engage in the process of theory development of SRT through hypothetical modelling. By performing the tasks in line with our expectations, the students engaged in hypothetical modelling: They proposed models (Task 4 and Task 5a), used these models to make predictions (Task 1, Task 5b and Reflection 6), and evaluated the models to come to accept or reject them (Reflection 2 and Reflection 6). As illustrated in the previous sections, this learning aim is also achieved.

In the classroom discussions that followed on the reasoning and reflection tasks, students and teacher together gave meaning to the outcome of the thought experiments that were performed in these tasks. The interviews conducted with teachers give an impression on what is said in these discussions. Bas (Class 4) described how his students proposed their own terms for the pre-instructional light propagation models. They talked about a speed of light relative to the old position of the lamp or relative to the new position of the lamp. The discussions on the two clashing models differed between the classes. Tjitske (Class 1) described a lively conversation in which the mismatch between ideas becomes apparent: *“[students] feel strongly that the speed of light should be constant, but they also think that if something starts to move, that this should have influence on the speed of light.*” Bas was less successful in activating this mismatch: “*They [two students with different propagation models] both explained how they came to their ideas, what their ideas were. Then I said, good, now we have two ideas. Now we should look what that leads to.*”

The teachers said that performing and interpreting the light clock TE (Task 6) was difficult for the students. Bas (Class 4): *“The difficulty is, that they did let the light go up and down in a way that it missed the mirror. In a way that light* *goes straight up, and the mirrors move. This was difficult for me too, except for explaining that it cannot be that something does not happen for one of the observers, […] but why this was so… No, this did not come spontaneous to the students."* Performing the TE was not problematic for Tjitskes students (Class 1), but it was difficult to interpret the outcome. Tjitske: *"They found this difficult to do. […] Not all students arrived to the conclusion by themselves […]. But all students accepted that the path is longer, and that, if the speed of light is the same for both observers, that it does take longer."*

Both Judith (Class 5-7) and Tjitske (Class 1) described the extra lesson in which the formula for time dilation was derived, as a concluding lesson for the students. All three teachers who performed this lesson said that the students liked the familiarity of an equation. Tjitske (Class 1): "*The equation was a logical consequence of what they had done before. The transition from the TEs to these tasks went very smoothly. I was surprised by how well it went. I have the impression that students could imagine the situations.*" Still, time dilation remained a difficult topic for some teachers. Bas (Class 4): "*Well, we did discuss this a few times, but it went a bit wrong on my part. I was mistaken a few times, which increased the confusion. So, in the end, students just said: Tell us what it is so we can use the equation.*"

In the posttest, students were asked to perform a TE deriving the relativity of simultaneity. This TE was presented as a question and not supported with a graphical representation. To interpret whether students used the light postulate in performing this task, their reasoning needs to consist of at least 4 correct elements and refer to 2 reference frames. This is only the case for 21 students. Of these students, ten answered in line with the light postulate which leaves 11 students who fall back to a pre-instructional light propagation model in this text-based task. Of the remaining 34 students, it is not possible to interpret which light propagation model they used to solve the task because they only referred to one reference frame, omitting the relativistic aspect of the task.

Students' learning may be influenced by the input they get from their teachers and fellow students: The context in which learning occurs matters. It is therefore interesting to check whether the student learning for the handed in tasks and the posttest, differs statistically significantly between classes. Because we are working with small numbers per group, Pearson's Chi-squared test for association is a suitable statistic for nominal data, which measures if two categorical variables are related. We tested the hypothesis that all classes do perform the tasks comparably, the results are given in Table 5.2. The results show that our hypothesis can be rejected for both items of Task 5 and the reasoning item in the posttest. This means that for these items, some classes perform better than others. The Chi-squared statistic does not specify which classes caused the rejection of the zero-hypothesis. However, Class 1 and 4 have a perfect score for Task 5b, applying the light postulate in the TE, whereas other classes have not. It is worth noting that for the reasoning tasks in the posttest, in these two classes a high number of students has four or more elements in their answer and refers to two reference frames. Still, in Class 4 most students do not answer in line with the light postulate and fall back to a pre-instructional light propagation model. In Class 1, most students also perform the posttest in line with the light postulate.

We tracked the learning paths of individual students in addition to analysing the results for each task per class. This is visualized in Figure 5.2. In this figure, each column represents the results for an individual student giving an impression how this student performed the tasks. Three learning paths are highlighted. These learning paths showcase students who did not reason with a consistent pre-instructional light propagation model, did not think the two formal models are plausible, and/or did not propose the light postulate. But these paths also show that these students did use the light postulate to perform thought experiments at a later stage. These examples illustrate that it is possible to have a variety of learning paths with our TLS leading to productive reasoning with the light postulate.

Table 5.2 The Chi-squared statistic with the degrees of freedom and two-tailed significance for the handed in tasks. The reliability of the statistic is limited because for some cells the minimum cell-count was lower than 5

Task	$\chi 2$	df	p
T1	10,242	6	0,115
R2a	2,719	6	0,843
R2b	8,175	6	0,226
T4	9,717	6	0,137
T5a	18,286	6	0,006
T5b	21,868	6	0,001
R6a	2,885	6	0,823
Posttest: elements	16,966	6	0,006
Posttest: reference frame	22,145	6	0,001
Posttest: light postulate	26,215	6	<0,001

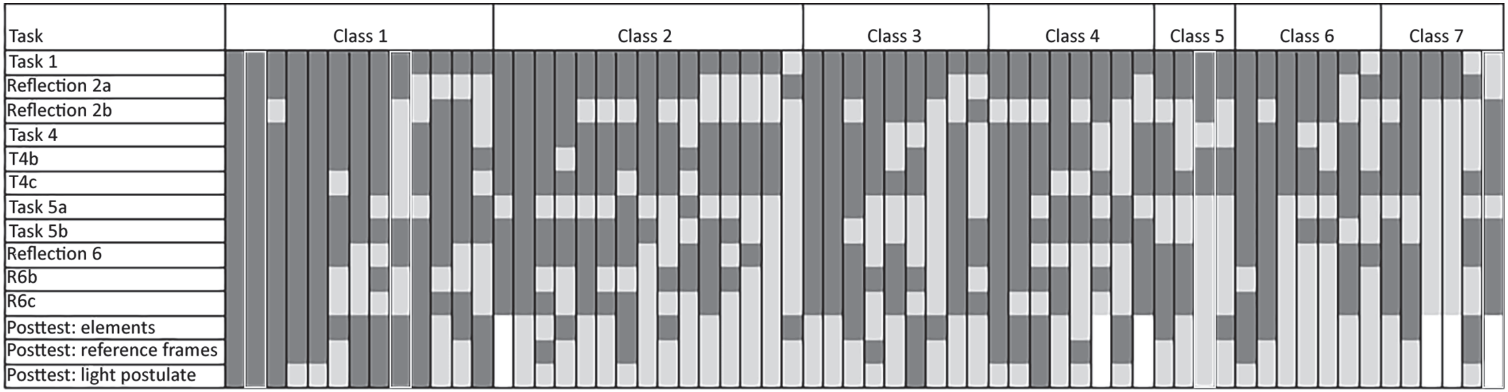

Figure 5.2 Individual student responses to the handed in tasks – two versions. Each vertical bar represents the learning path of a student. The dark cells represent answers in line with our expectations, the light cells represent answers not in line with our expectations. The white cells represent missing answers, since not all students who handed in all five tasks also performed the post-test. Results of student 2 and 9 in class 1 are highlighted, as well as student 3 in class 5 and student 6 in class 7

The students in this sample have performed a TE deriving the relativity of simultaneity twice. Once in Task 5, and once on the posttest in a reasoning item. The main difference between the two TEs is how they were presented to the students. It is therefore interesting to take a closer look at further differences between the TE's other than the point in time at which the students performed them, because it may give insight in what makes relativistic reasoning difficult for secondary students. The first difference between these TEs is that Task 5 was supported by a graphical representation, whereas the TE in the posttest was not. The graphical representation provided an overview of the position of objects and observers for subsequent moments in time. This helped the students to imagine the initial setting of the TE and to keep track of all the relative movement, and supported students in reasoning with light propagation. The second difference is that the phases of TE in Task 5 were also separated in several activities: Deductive reasoning with the light postulate for two different observers and obtaining a task-outcome. Subsequently checking this reasoning with a correction sheet, and finally individual and group reflection on the outcome of the TE. In contrast, the TE in the posttest was presented as one question that required students to perform the subsequent phases of the TE independently. The number of students that performed the TE correctly for Task 5 is much higher in the posttest. It must be noted that Task 5 only addressed the first phase of the TE. However, the scoring of the posttest also focussed on this first phase. These results suggest that the graphical representation is supportive for students to perform a relativistic TE and that separating the phases of a TE into different activities is helpful for secondary students to engage in relativistic reasoning.

5.4.3. Comparing students' learning outcomes of TLS to regular approach

In this section we will compare the learning outcome of students taught with the TLS (intervention group) to students taught with regular teaching approaches (control group). To that end the answers to the reasoning and computational items collected in the post-test are evaluated. We will first discuss the results of the reasoning task and conclude with the computational items. The results are summarized in Table 5.3.

Both the reasoning and the computational items are coded in two ways. First, the students' answers are graded with points. In addition, the items are also coded more qualitatively. The reasoning item was coded with the number of correct answering elements, the number of reference frames and if the students' answer was in line with the light postulate. The computational items were given a code that indicated the students identified the correct rest-frame in both tasks.

Table 5.3 Mean scores and frequencies of reasoning and computational items in the posttest

Task	Overall score	Intervention group	Control group	Difference One-way ANOVA or Pearson's χ^2
Reasoning items (N)	312	143	169	
Mean Total score (sd)	1.21 (1.38)	1.17 (1.36)	1.24 (1.41)	F (1,312) = 0.185, p = 0.668
4 or more correct elements	161/339	72/159	89/180	χ^2 (1, 339) = 0.586, p = 0.444
2 reference frames	123/339	56/159	67/180	χ^2 (1, 339) = 0.146, p = 0.702
Light postulate	73/339	35/159	38/180	χ^2 (1, 339) = 0.041, p = 0.840
Computational items (N)	265[a]	94	171	
Mean Total score (sd)	2.72 (2.37)	1.88 (2.21)	3.19 (2.32)	F(1, 265) = 19.7, p < 0.001
Correct rest frame	71/286	14/108	57/178	χ^2 (1, 286) = 13.1, p < 0.001

[a] Not all students made both the reasoning and the computational items. Therefore, the total number of students is not equal.

The maximum score for the reasoning items was 5 points. The two conditions are comparable on the obtained score for the reasoning items with an average of 1.2 points (sd = 1.4). A one-way ANOVA test shows that there is not a significant difference between the intervention group and the control group for the reasoning score ($F(1, 312) = 0.185$, $p = 0.668$). However, the difference between classes in the control group is statistically significant ($F(9, 169) = 3.733$, $p < 0.001$), showing that this was not a uniform group.

The qualitative analysis of the first reasoning item shows the same pattern for the total sample, as described for the intervention group in the previous section. The two conditions are statistically comparable. In their answers, most students did not refer to two reference frames. This aspect of relativistic reasoning is apparently not something the students performed without an explicit prompt. An alternative explanation is that the students did not recognize the relativistic context of the item. This is highly unlikely, since the students knew they were tested on their understanding of relativistic concepts. Of the students who referred to two reference frames it is possible to make a distinction between reasoning with a pre-instructional model and reasoning with the light postulate. Half of these students performed the TE in line with a pre-instructional light propagation model.

The maximum score for the computational items is 6 points. The mean computational score equals 2.48 points ($sd = 2.39$). The control group has a statistically significant higher score on these items than the intervention group ($F(1, 291) = 41.2, p < 0.001$, Table 5.3). An explanation for this result is that two classes of the intervention group were not taught this equation because the teacher did not give this final lesson. If we leave these classes out of the analysis, the mean computational score equals 2.72 ($N = 265$, $sd = 2.37$). The control group performed the computational items better than the intervention group. It is worth noting that the average score of 3.2 out of 6 points the control group obtained is not very high in itself. A closer look shows that most students did not identify the rest frame correctly for both items (Table 5.3). Still, the number of students who assigned rest frames correctly is significantly higher in the control group than in the intervention group.

5.5. Conclusion and Discussion

In this chapter, we have described the adaptation of a small-group TLS for the classroom and the evaluation of the resulting classroom TLS. The TLS is based on creating a meaningful mismatch between pre-instructional light propagation models to engage students in productive reasoning with the light postulate. This is done in tasks in which students perform thought experiments and engage in hypothetical modelling with their pre-instructional light propagation models and the light postulate.

The first research question addressed how the small-group TLS can be adapted for the classroom setting. This was done in close collaboration with teachers, who participated as co-designers and implemented the TLS in their own lessons, ensuring classroom feasibility of the design. The focus of this process was to implement how all students can actively participate in performing TEs in the design. This was done through designing explicit activities for each phase of performing a thought experiment. The lesson was based on a central question for each lesson. A reasoning activity provided students with information to answer this lesson question. A reflection activity was designed with the aim of having students answer the lesson question. In this activity, students reflected on the task outcome individually, in pairs and finally in a classroom discussion. This design intends to stimulate all students engaging in all steps of performing a TE.

The second question addressed the evaluation of the learning aims of the newly designed TLS. We found that the TLS was successful in engaging the students in productive reasoning with the light postulate. Most students proposed the light postulate as a new propagation model and used it to perform and interpret TEs, both in the TLS and in the posttest. The students had different learning paths and were able to reconnect to the TLS when they missed a task. There were differences between the classes in the intervention group for applying the light postulate to perform a TE in lessons and at the reasoning items in the posttest. The attitude of the students, something all teachers in the intervention group struggled with, combined with the high number of absent students in each class, may have influenced the extent in which teachers were successful to engage the students in a fruitful classroom discussion to interpret the outcome of the individual reasoning activities and as a consequence, also influenced how students performed these tasks. The students were asked to derive the relativity of simultaneity twice. In the TLS, many students performed well for this task, whereas this number was much lower in the posttest. The redesign of thought experiments for the full classroom setting in this way seemed therefore to be successful in supporting students to perform relativistic thought experiments themselves.

The third question addressed how the learning outcome of student learning with the TLS compared to that of students taught with regular approaches. To this end, we used a pre-/posttest setup. On the reasoning items, we found no differences in how the students scored between the intervention group and the control group. It turned out that the relativity concept inventory (RCI, Aslanides & Savage, 2013) that was intended to probe students' conceptual understanding of relativity was unsuitable for this audience. We therefore cannot give a more detailed description on this aspect. The performance on computational SRT questions was better in the control group than in the intervention group. This finding reflects that the intervention group spent very little time on using the formula for time dilation. However, few students in both conditions correctly identified the rest frame for both tasks. This result demonstrates that an approach based on using formulas did not result in the students of the control group grasping the relativistic aspect of the tasks.

5.5.1. Reflection on differences between classes and conditions

For some tasks and items, there were significant differences in performance between groups. Here we will discuss some possible explanations for these differences.

In the intervention group, there was a statistically significant difference in the number of students per class that performed Task 5 and the reasoning item in the posttest correctly. There are two possible explanations for these differences in performance: The fraction of students with perfect attendance and the learning atmosphere in the classes. This first parameter does not provide a sufficient explanation. Classes 3, 4, 6 and 7 have a comparable attendance fraction. However, Class 4 performs better than the other three classes. Class 1 and 2 also have similar fractions for perfect attendance, and also these classes do not perform Task 5 and the posttest comparable.

The learning atmosphere in the classes may be more sufficient to explain the significant differences on the performance of Task 5 and the posttest. The teachers of Class 1 and 4, Tjitske and Bas, described their classes as “more difficult than last year” (Tjitske and Bas) whereas the teachers of the other classes, Nienke, and Judith, described their students’ attitude as “done with the school year” (Nienke, classes 2 and 3) and “actively sabotaging exercises because they did not feel like participating” (Judith, classes 5-7). It is likely that the teachers of the better performing classes had more success in creating a fruitful teaching and learning process. In addition, Bas described that his students did go through the motions of the exercises but were waiting for their teacher to tell them the answers. This may explain why his students scored very low on using the light postulate in the posttest, contrary to Tjitske’s students. The students in class 4 did not confront their pre-instructional ideas and fell back to using them once they had to solve a task in a new context.

The control group performed the computational items significantly better than the intervention group. A possible explanation for this difference is the time teachers in the intervention condition spent on performing such tasks. The classes of the intervention group only spent one lesson on deriving the formula of time dilation and practicing with it. Regular approaches have a stronger focus on applying formulas. Therefore, it is maybe unsurprising that the control group has a higher average score. However, the number of students correctly identifying the rest frame of the tasks was low over the entire sample. This result underlines that a teaching approach focussing on the use of equations, does not necessarily result in applying these equations correctly in relativistic situations.

5.5.2. Limitations

Many adaptations from the small-group version of the TLS to the classroom version, aimed to make the role of the teacher more limited. Reasoning tasks and reflection tasks were extensively described in the teaching materials. However, in the classroom version the teacher still plays a crucial role guiding the learning process. The teacher introduced the learning question, explained why the reasoning task will provide students with the tools to answer this learning question and guided a classroom discussion in such a way that all various students' ideas were mentioned and discussed before drawing a conclusion. The role of the teacher was explicitly described in the teacher materials of the design. The teachers of the intervention group mentioned this role was new for them, and some of them struggled with conducting these classroom discussions. The scope of this study is limited to students' individual learning outcomes. The classroom discourse that preceded this learning and how teacher conduct shaped this discourse is an interesting topic for a different study.

We have seen that in all classes, many students missed one or more lessons. In our analysis of the handed in tasks we focussed on the students who were present for all lessons. The results on student learning throughout the lessons is therefore limited to this group of students and excludes student learning for students who missed one or more lessons. However, the fact that a fraction of the class missed a lesson may impact the learning of the students who were present in that lesson as well. It may be difficult for teachers to involve all students in a classroom discussion that builds on insights from what has been learned thus far if many of the students have been absent in a previous lesson. If we want to design teaching approaches that withstand the test of educational practice, the design should allow for students to miss part of the lessons without it directly obstructing their learning, as illustrated by the high number of students missing part of the lessons in this study. However, to what extent students are successful in achieving the intended learning aim when they miss part of the lessons does not only depend on the design itself. Students' personal motivation, practical circumstances and how teachers guide students outside of class hours also influences this.

We did not acquire a broad view of students' conceptual understanding of relativity because it turned out that the RCI (Aslanides & Savage, 2013) was not suitable to assess this for the students participating in our study. Besides the teaching approach, there are two differences between this study and the validation study of Aslanides & Savage (2013) for the RCI, that offer an explanation. First, the level of students involved in the validation study were first year university physics students and high academic achievers, being the top 5% of the country. The pre-university level science track students in our study are the top 18% of the Netherlands. Second, the duration of the intervention differs between the two studies. Students in the validation study received between 15 and 27 hours of education, in contrast, students in our study received 4 to 10 hours. Researchers who want to use the RCI to test conceptual understanding of students, should therefore take these two aspects into consideration before using the RCI to probe students' conceptual understanding of SRT.

5.5.3. Comparing the results to other studies

The underlying assumption of the first reasoning task was that students would use a consistent pre-instructional light propagation model to perform the task. The results of the first reasoning task show that not all students work with such a consistent model[1]. This is in contrast with our expectations based on the findings of our study "Pre-instructional reasoning with light propagation in relativistic contexts" (Kamphorst et al., 2019). In this previous study we showed that students use a consistent pre-instructional light propagation model in contexts with different relative movement with a constant speed relative to the lamp or the graph paper. These results can be explained by the procedure used in the pre-instructional reasoning study. In this study, the students performed a reasoning task in three different contexts. As part of the protocol, the students were asked to compare their three answers. For students who would reason with an inconsistent model over the different contexts, this was often a prompt to change their answer in one of the tasks, resulting in a consistent propagation model. In the study we describe in this chapter, we presented the students with four contexts, allowing us to make a distinction between a constant speed relative to the lamp and to the room. In addition, comparing the answers over different contexts was done in the reflection activity after student answers were collected. Therefore, eventual changes in students' models are not registered. However, this result demonstrates that students pre-instructional reasoning is not a rigid, consistent theory, but is rather adaptive to context and has a more fluid nature (Disessa, 1996; Disessa & Sherin, 1998).

The classroom TLS is a design iteration of the small-group TLS. The reasoning activities and learning aims remained similar, although the way tasks are presented to students changed. The method of assessment is slightly

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[1] This number is limited: Of the 174 students performing the first task, 23 did not reason with a consistent light propagation model.

different between the two studies: In the small-group setting we observed the entirety of student learning, whereas in the classroom setting we probed student learning with 5 tasks. This resulted in a slightly more limited view on what the students did in the lessons. However, we can still compare how successful the two approaches are in introducing the light postulate. In the small-group setting all students applied the light postulate and could use this propagation model to obtain outcomes of thought experiments and interpret them. Thirteen out of 15 students developed confidence in the light postulate, only two students doubted whether their pre-instructional model should be preferred over the light postulate. In the full classroom setting, two thirds of the students in the intervention group used the light postulate to perform and interpret thought experiments. This shows that it is difficult to obtain the same learning results in a more complex setting with more students.

If we compare the results of students' reasoning with the light postulate with other studies, two thirds of the students using the light postulate is a positive result. Gousopoulos et al. (2016) reported that 67% of 45 non major physics university students can give a correct definition of the light postulate but failed to apply it correctly in a reasoning task. Exact data on the number of students who do correctly apply the light postulate after regular instruction are not mentioned. Villani & Pacca (1987) reported that 20/24 students involved in MSc and PhD programmes in physics- and science education answer contradictory to the light postulate on a reasoning question involving light propagation. It is not reported how long after instruction these questions were administered.

5.6. Outlook

In this study we reported on bringing a teaching and learning sequence for SRT to the classroom. This TLS introduces the need for a new light propagation model through engaging students in the process of hypothetical modelling. Students solve the need for this new light propagation model by proposing the light postulate. By designing separate teaching and learning activities for each phase of the TE, all students in the class had the opportunity to actively engage in performing TEs. We have shown that this TLS was successful in engaging the students in productive reasoning with the light postulate in the tasks that are part of the TLS. In this first attempt to bring a new teaching approach to the classroom, the students in our intervention group performed the reasoning tasks in the posttest comparable to a control group that was taught with regular approaches. Attention to what characteristics in the classroom discourse support student learning may even improve on this result.

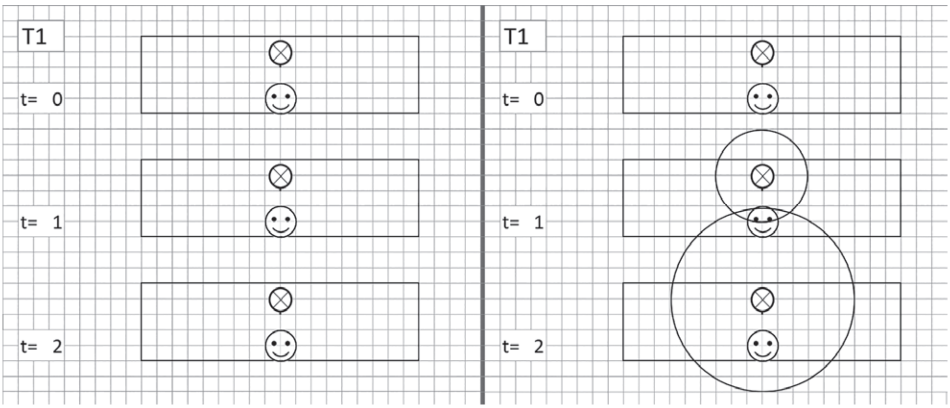
Appendix A – hand-in tasks

Task 1

In this task, we look at a room with a door at each side. A lamp hangs in the middle of the room and an observer is somewhere in the vicinity of the room. The lamp emits a light flash at timestep 0 and turns off afterwards. You will figure out at which timestep(s) the light flash will hit the doors, by drawing in a diagram.

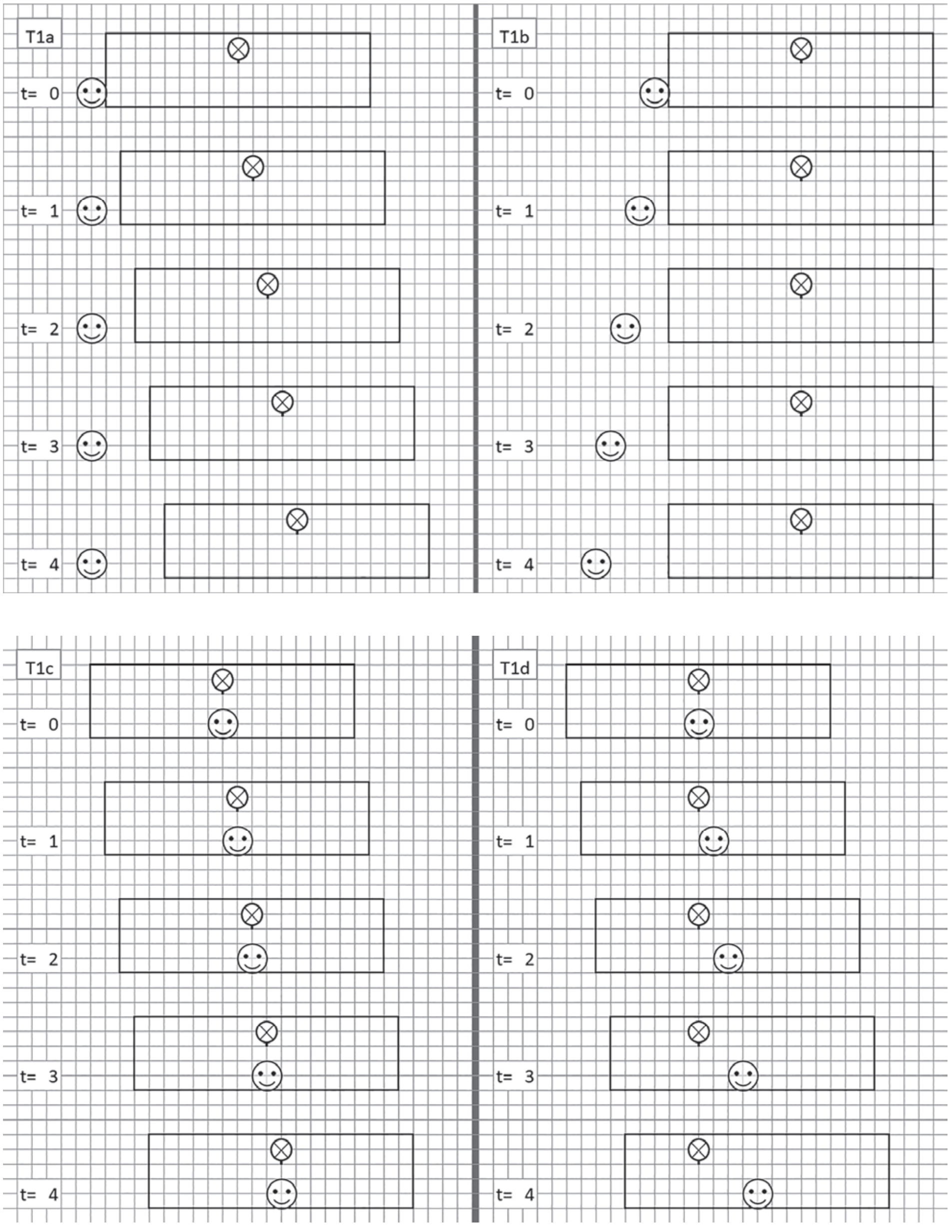
The diagram in this task is similar to the diagrams you worked with before. Room, doors, lamp and observer are pictured at subsequent moments in time. An example is shown in the left figure.

You will draw the light emitted by the lamp, yourself. Light propagates with three squares per timestep. The right figure shows how you can draw this.



The task you are about to make, consists of four diagrams, in which the observer is outside (Diagrams T1a and T1b) or inside (Diagrams T1c and T1d) the room. You may assume that the observer can look inside the room. In this task, the observer, the room or both are moving.

1. Draw the light in the diagrams all timesteps.
2. Give the timestep(s) light arrives at the doors.


T1a
t= 0
t= 1
t= 2
t= 3
t= 4
T1b
t= 0
t= 1
t= 2
t= 3
t= 4
T1c
t= 0
t= 1
t= 2
t= 3
t= 4
T1d
t= 0
t= 1
t= 2
t= 3
t= 4

Reflection 2

You used two drawing rules in making and correcting Task 2. These drawing rules lead to different predictions for the moment you think that the lamps have emitted a light flash.

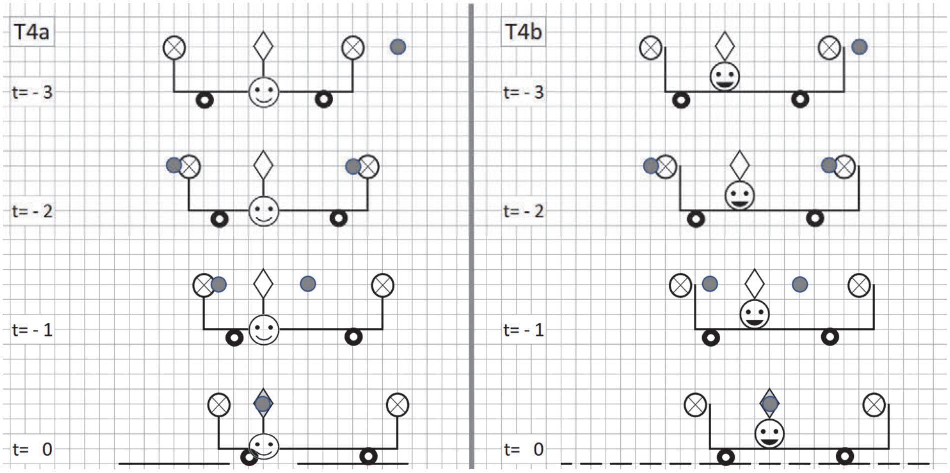
1. Which drawing rule(s) is/are correct? Choose the answer that is closest to your ideas:
    a. The drawing rule I used for Task 1 is correct, the other is not.
    b. The drawing rule I used for Task 1 is incorrect, the other can be correct.
    c. The drawing rule I used for Task 1 AND the other drawing rule can be correct.
    d. The drawing rule I used for Task 1 OR the other drawing rule can be correct.

A researcher uses both drawing rule 1 and drawing rule 2 to make a prediction. The predictions are not identical.

1. Can both predictions be correct? Explain your answer.
2. Can both predictions be explained with the same experiment? Explain your answer.

Task 4

These diagrams show how light propagates. These results are confirmed by experiments.



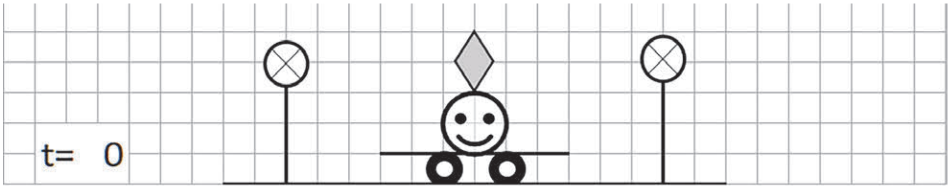
The drawing rules that are used to construct these results, cannot be used to make predictions that are correct in all situations.

1. Propose a new drawing rule that would allow you to reproduce these results.

Task 5

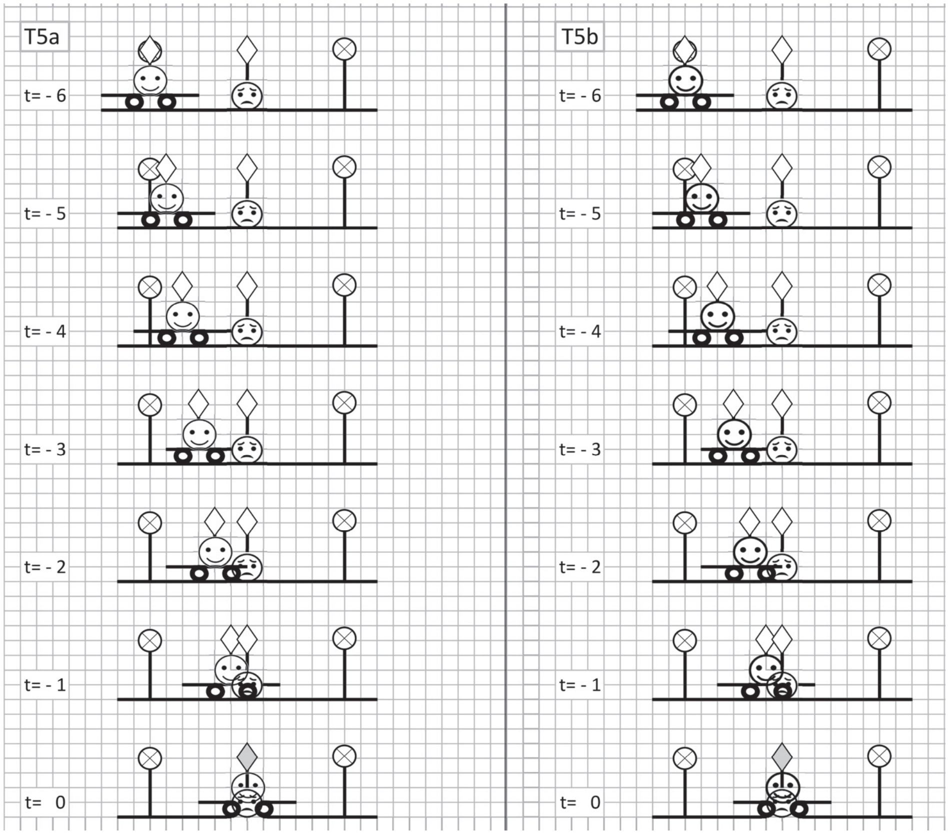
In this task, we study an observer with a measuring device. The measuring device registers the moment when two light flashes arrive simultaneously. You are going to figure out when the light flashes were emitted. The light flashes are emitted by two lamps, which will switch off as soon as they emitted their light flash. The task consists of a separate question, two diagrams and a number of questions in which you reflect on the outcomes you obtain in the diagrams.

In this task, you reason from the perspective of the observer. Below you can see part of the diagram. The diamond at the at the observer depicts the measuring device. A gray diamond indicates that the light flashes have been registered by the measuring device. The lamps are depicted with the electric circuit symbols of a lamp. Again, light has a speed of three squares per time unit in the diagram.



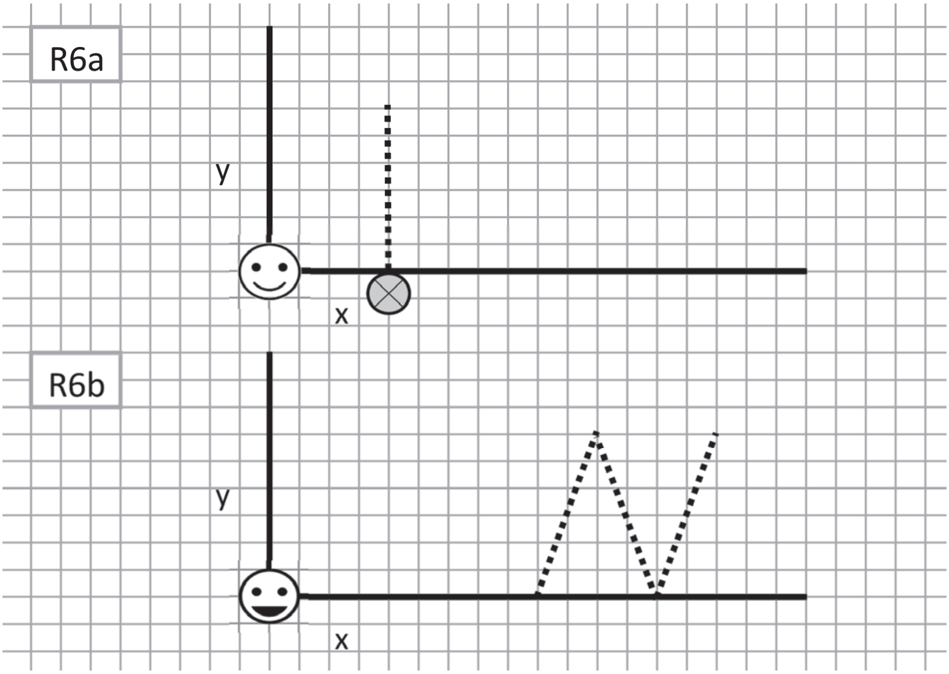
Try to be as complete as possible in your answers to the questions. Make your train of thought transparent to someone else.

1. Explain in your own words how light propagates.
2. The final time unit $t = 0$ of diagram T5a shows that the two light flashes arrived at the device of the researcher. Determine by drawing in the diagram at which place and time the lamps were switched on according to this observer.
3. We consider the same situation, this time from the perspective of a different observer (diagram T5b). This observer is depicted with a sad smiley-face. At which place and time were the lamps switched on according to this observer?



Reflection 6

The thought experiment of Task 6 is about the time interval between two events: Emitting a light flash by a lamp (event 1) and the light flash returning at the bottom mirror (event 2). In the figure below, the light path relative to observers A and B is shown.



1. What is the duration of the time interval between the two events according to observer A (R6a)?
2. Will observer B (R6b) measure the same duration? Explain why or why not, and what the possible difference with observer A is.

Appendix B – Codebook for hand-in tasks

Table 1 Codebook hand-in tasks

Task/Reflection	In line with our expectations	Not in line with our expectations
1: All questions combined	The student's answer over all diagrams can be interpreted as a constant speed relative to the Lamp, Room, Graph paper or Observer.	The student's answer over all diagrams cannot be interpreted as a constant speed relative to one reference frame over all situations, or cannot be interpreted.
2a: Question 1	C, D	A, B
2b: Question 2 and 3	The student answer can be interpreted as that the two drawing rules exclude each other if they do not lead to the same outcome.	The student answer can be interpreted as that the two drawing rules do not exclude each other.
4: Question 1	Students propose their own version of the light postulate. In this, they explicitly mention a constant speed relative to the observer.	Students propose a pre-instructional model or describe two models that work in one of the situations.
5a: Question 1	Students propose their own version of the light postulate. In this, they explicitly mention a constant speed relative to the observer.	Students do not propose the light postulate.
5b: Question 2 and 3	The student's answer over both diagrams can be interpreted as a constant speed relative to the observer.	The student's answer over both diagrams cannot be interpreted as a constant speed relative to the observer.
6: Question 1 and 2	Students mention that the time interval for the observer of question 2 is longer than that for observer 1.	Students mention that the time intervals are the same for both observers, or that the time interval for observer 2 is shorter.

Chapter 6
General Discussion

6.1. Research overview and main findings

Special Relativity Theory is one of the famous and iconic theories in physics. The theory is prototypical for how knowledge development in physics can take place, deriving new concepts form a set of basic ideas. Even more, the theory represents a transformation of how physicists look at the world. Time and space were always regarded as two independent quantities, with an absolute nature. The introduction of Special Relativity combined these quantities in one unified spacetime that is observer dependent. The consequences are far reaching. The theory introduced counterintuitive phenomena, such as time dilation, length contraction and the relativity of simultaneity. Moreover, interpreting the world around us was no longer left to the senses, but had to be done through interpreting measurable quantities.

It is desirable that secondary students get the opportunity to acquaint themselves with these ideas. In recent years, the interest to introduce Special Relativity Theory (SRT) in secondary education has grown. In the Netherlands, SRT was introduced in the upper-level secondary curriculum in 2013. However, little is known on student learning with this topic. A recent review on the available literature (Alstein, Krijtenburg-Lewerissa & van Joolingen, 2021) shows that learning relativistic concepts is difficult and gives rise to some robust misconceptions. Therefore, when introducing SRT at the secondary level, teaching approaches should be designed to address these difficulties.

The aim of this research project was to contribute to the scientific knowledge base of learning SRT in the upper years of pre-university level secondary physics education through the design and evaluation of a teaching and learning sequence. To that end we developed a reasoning tool, the Event Diagram. This diagram supports secondary students to perform relativistic thought experiments (**Chapter 2**). This tool was used to study students' pre-instructional reasoning with light propagation (**Chapter 3**). These efforts served as a starting point for the educational reconstruction of SRT we conducted to design a Teaching and Learning Sequence (TLS) introducing the light postulate to secondary students (**Chapter 4**). The tasks in the TLS were based on relativistic thought experiments supported with Event Diagrams. The TLS was evaluated in a small-scale teaching experiment. In the final study, the TLS was redesigned for and evaluated in the classroom (**Chapter 5**).

6.1.1. Supporting the performance of thought experiments with Event Diagrams

In **Chapter 2** we introduced a visual representation that supports students in relativistic reasoning: The Event Diagram (ED). An earlier version of the ED was previously proposed by Scherr (2001) and we adapted it to support students in performing thought experiments (TEs). In this chapter we also presented three examples in which relativistic TEs are supported with an ED.

It is expected to be difficult for secondary students to perform TEs themselves for several reasons. First, the way TEs are often presented obscures the reasoning that leads to the outcome and overall conclusion of the TE. Second, performing relativistic TEs involves reasoning with the absolute speed of light, something that is notoriously difficult for students in all levels of education. Third, to perform a relativistic TE students need to evaluate events relative to two reference frames in relative motion. This requires students to keep track in their minds of relative movement while reasoning with difficult and counterintuitive concepts. We proposed that an external representation of spacetime in the form of an ED can support students in performing relativistic TEs themselves.

EDs are representations of spacetime that show the position of objects and events at several subsequent moments in time, from a specific reference frame. Scherr's version of the ED, visually organizes the information of the assignment but does not explicitly support student reasoning with light propagation. To address this, we added three features with respect to this version. We placed the EDs on a grid and we added more pictures to the ED, showing the position of objects and events at regular time intervals. These two features combined, allow to interpret the speed of moving objects and to draw the position of a light flash in the ED, thus supporting the stepwise reasoning with light propagation to perform TEs. Finally, we did not show the answer of the TE in the diagram, this further supports students to perform the deductive reasoning of the TE themselves to obtain an outcome.

An important contribution for education is that we aligned the phases, intrinsic to performing TEs, with our task design. The first stage of performing a TE, sets the stage of the TE. In this stage, the initial situation is described, the theoretical basis defined and a central question formulated. In our tasks, the stage is set by the ED and the central question is presented in the task. The theoretical basis can be either chosen by the student or instructed by the teacher. In the second TE stage, the central question is answered by means of deductive reasoning from the initial setting with the theory at hand, obtaining an outcome. The deductive reasoning in our tasks is performed by drawing the position of light flashes in subsequent pictures of the ED thus finding the time and position of events. In the final and third stage, an overall conclusion is drawn based on the task outcome of the TE. Overall reflection, giving meaning to the outcome of the TE is done in dialogue with the teacher.

6.1.2. Pre-instructional reasoning with light propagation

The aim of the study described in **Chapter 3** was to elicit the underlying reasoning students use when reasoning with light propagation. We therefore had the following research question: *Using Event Diagrams, in what ways do secondary education students reason with light propagation in relativistic situations prior to instruction?* To answer this question, we performed a clinical interview study in which 15 11th grade pre-university level students were asked to solve a reasoning task, drawing light propagation in EDs. The students performed a total of six task. Three versions of a non-relativistic task and three versions of a relativistic task in which an observer and light source had a relative speed.

The students in our sample made their reasoning explicit and used the EDs to obtain task outcomes by stepwise reasoning with light propagation in the ED. The students used the following procedure: They determined the distance light had moved since the previous timestep and used this to determine the position of the light flash for the subsequent moment in time. After instruction, 14 out of 15 students used the EDs to perform the reasoning task. One student did not use the EDs to solve the reasoning tasks. These results led us to conclude that students can learn to productively use EDs as a reasoning tool.

The students used different light propagation models to solve the relativistic reasoning tasks. They either reasoned with a constant speed of light relative to the graph paper-frame or with a constant speed relative to the lamp-room frame. The students who reasoned with a constant speed of light relative to the paper frame focussed on the movement of objects, whereas the students who reasoned in the lamp-room frame focussed on the position of objects.

Independent of the pre-instructional light propagation model the students used to perform the reasoning tasks, they evaluated light speed relative to several reference frames. In physics applying the light postulate would result in finding the same value in all frames. However, the students reported different speeds when describing the propagation of a light flash in different reference frames. Nonetheless, these students, like physicists, said that the speed of light is the same for everybody. This must not be mistaken for students understanding or quoting the light postulate. It just means that, according to students, all observers agree on a reference frame (for instance the lamp-room frame) in which the speed of light has its finite value.

An important result was that some students changed frames while performing the relativistic reasoning tasks. These students either became aware of the other frame and found this a more plausible light propagation model than their initial choice or they experienced some conflict between the speed of light as a maximum and their own answer. For education, in which the aim is to change students reasoning with pre-instructional light propagation models into reasoning with the light postulate, explicitly problematizing reference frames may proof to be a suitable approach.

6.1.3. Educational Reconstruction of Special Relativity Theory for Secondary Education

In **Chapter 4** we described the design and evaluation of a teaching and learning sequence, drawing on this conflict between pre-instructional light propagation models. We proposed that SRT is an excellent topic to familiarize students with the process of scientific knowledge development. Simultaneously, SRT education should build on students' pre-instructional ideas to help them bridging the gap between their understanding and the physics concepts. In this chapter we answered the following research question: *How can learners in secondary education develop a conceptual understanding of SRT through engaging in a process of physics theory development?* To answer this research question and meet this dual learning aim in our eventual design, we performed an educational reconstruction of SRT for secondary education. This resulted in a content structure for instruction that was translated into a Teaching and Learning Sequence, presented in the form of a Hypothetical Learning Trajectory (HLT).

In the first part of Chapter 4, we presented the educational reconstruction and the HLT. We analysed SRT through the lens of the Dutch curriculum goal and Lakatos' view of scientific research programmes. In this analysis, we identified the overall aim of SRT to be to expand Galilean's relativity principle to the domains of optics and electromagnetism, thus solving a perceived asymmetry in Maxwell's electromagnetism. To this end, the light postulate is used in a process of hypothetical modelling, deriving relativistic phenomena from the basic concepts of event and reference frame. This process is guided by the epistemic value of the relativity principle. We aimed to maintain this mode of reasoning in the educational design but judged the perceived asymmetry in electromagnetism unsuitable for secondary students.

Based on the analyses from the theoretical and of the learners' perspective, we formulated an overall learning aim. The TLS should result in productive reasoning with the light postulate for students. This is defined as using the light postulate to derive relativistic phenomena. We proposed that students should attain the following insights to experience a need to start reasoning with a new light propagation model:

1. (Pre-instructional) light propagation is always relative to a reference frame,
2. Different choices for this reference frame are possible,
3. Predictions differ dependent on the choice of reference frame, and
4. Their current reasoning leads to wrong/inconsistent predictions.

For adopting the light postulate for productive reasoning, students should:

5. Change the reference frame for light propagation to the reference frame of the observer,
6. Experience that this new light propagation model solves the problems they experienced with their pre-instructional models, and
7. Explore the consequences of this new propagation model.

These two phases of theory development (1-4 and 5-7) were addressed in the two parts of our educational design, illustrating how the key ideas and theory development of SRT can be reconstructed into a content structure for instruction (Table 6.1). The tasks designed as part of the TLS based on this content structure, support students to engage in hypothetical modelling with their pre-instructional light propagation model and with the light postulate.

In the evaluation of the TLS, we have shown that the design allowed the students participating in our study, to develop a conceptual understanding of SRT and the light postulate in particular. Thirteen out of 15 students developed confidence in the light postulate as a propagation model for productive reasoning. They used the light postulate to derive other relativistic concepts and, in this process, interpreted velocity, the time of an event and duration relative to a specific reference frame. The students engaged in hypothetical modelling activities with their pre-instructional light propagation model and the light postulate in the lessons. Thus, showing that a teaching sequence based on hypothetical modelling with students' pre-instructional light propagation models can engage students in the theory development of SRT.

6.1.4. Introducing the light postulate in the secondary classroom

The aim of the study described in **Chapter 5** was to further adapt the TLS described in Chapter 4 for use in the classroom[1]. We address three research questions in this chapter: (1) *How can the small group TLS be adapted for the classroom context?* (2) *To what extent is the intended learning achieved with the classroom TLS?* And (3) *How do learning outcomes with the classroom TLS compare to those of traditional teaching approaches?*

To answer these research questions, we conducted a design study in which we closely collaborated with eight teachers who were also involved in the evaluative study and an evaluative and comparative study. In these studies, a total of 389 students in 17 classes taught by 12 teachers participated. In the classroom version, the tasks in which students perform thought experiments were split up in a reasoning task and a reflection task. The evaluation of the answers of 62 students to these tasks showed that the TLS resulted in productive reasoning with the light postulate for the majority of the students in this new classroom context. The comparison between student answers to the same TE performed in our task format with an ED and formulated as an open question without an external representation, suggests that our task design supports students in performing relativistic TEs in the classroom context. This study was a first attempt to bring our TLS to the classroom. Nonetheless, the intervention group students performed reasoning tasks at the same level as students taught with regular approaches. Attention to what teacher actions and characteristics of classroom discourse support student learning, may even improve upon this result.

[1] The teaching materials are published at www.fisme.science.uu.nl/toepassingen/28984/

Table 6.1 Overview of the Teaching and Learning Sequence

Content structure for instruction	Hypothetical Learning Trajectory
Part 1: Introducing the need for a new light propagation model - Becoming aware of the limited predictive value of pre-instructional light propagation models	
Hypothetical modelling with pre-instructional model	
1. Becoming aware of the initial light propagation model and the role of reference frame in this model,	Task 1: Exploring initial ideas
2. Becoming aware of other options for reference frame (through the introduction of formal models) and as a consequence questioning the reference frame of the initial model,	Task 2: Confronting inconsistencies
3. Becoming aware that the two formal models, and as a consequence the initial propagation model, do not have predictive value in all contexts,	Task 3: Evaluating predictions
4. Therefore, rejecting the reference frame of these models and making it plausible to introduce a new model.	
Part 2: Developing confidence in the light postulate as a propagation model for productive reasoning	
Hypothetical modelling with light postulate and exploring its consequences	
1. Proposing a new, consistent light propagation model which is therefore plausible: The light postulate,	Task 4: Proposing the light postulate
2. Confirming the new model solves the problem of limited predictive value,	
3. Using the light postulate to make predictions in new contexts,	Task 5: Exploring counterintuitive consequences
4. Deciding to keep using the model,	
5. Deriving new concepts with the light postulate.	Task 6: Exploring the consequences for time

6.2. Contributions

The motivation for this research project was to develop a conceptual teaching approach for Special Relativity Theory that introduced relativistic concepts, in particular the light postulate, to secondary students. In the previous chapters of this dissertation, we have shown that our approach successfully introduced the light postulate to secondary students. Furthermore, we aimed to contribute to both the scientific knowledge base and educational practice with the project. In this section, we will discuss the contributions to these two fields.

We used a design approach *combining the frameworks of the Model of Educational Reconstruction (MER) and Design Research (DR)*. This combination stimulated us to create a detailed view on student learning processes and the content structure of SRT on the one hand and look for design guidelines that can inform future educational design on the other hand. DR and MER served as two complementary methodological frameworks. The framework of MER provided a broad perspective on theory, including the history and philosophy of physics, on the one hand and teaching and learning perspectives on the other hand. DR provided a structure to include the input of practitioners and design hypotheses. The combination of these two frameworks seems especially fruitful for topics that are not part of a longstanding teaching tradition (Kamphorst & Kersting, 2019). For such topics, design researchers cannot appeal to experts in the field. However, to ensure that the design is suitable for real education contexts, the input of practitioners is essential. The framework of MER does not explicitly include this perspective. DR does not involve the theory perspective explicitly, which is a valuable contribution of MER.

In the first empirical study we addressed *students' pre-instructional reasoning with light propagation*. This study has two main contributions. The first contribution considers the pre-instructional models themselves: Pre-instructional reasoning with light propagation for this age group was not described before. The second contribution is that students do not all use the same pre-instructional model (a constant speed relative to the lamp-room frame and relative to the paper frame). The available literature mentions that tertiary students after instruction often do not reason with the light postulate. However, this literature either is not clear on what students do instead (Gousopoulos, Kapotis, & Kalkanis, 2016), or suggests that all students have the same absolute space in mind for a constant lightspeed (Villani & Pacca, 1987).

Another contribution of our research is the development of the *Event Diagram as a reasoning tool*. We have shown that the ED in this form can be used both as an instrument to elicit student reasoning with light propagation and support students to perform the deductive reasoning of thought experiments themselves. Our *task design that allows students to perform TEs in classroom* is in line with this contribution. The literature on TEs in education addresses mainly the philosophical aspects of performing TEs and possible contributions of student learning, but there are little studies that describe student learning with TEs. We have shown that performing TEs can contribute to students' understanding of relativistic concepts.

The main contribution of this research project for the educational practice is the Teaching and Learning Sequence we designed and evaluated. The TLS offers a *conceptual approach to introduce the light postulate to secondary students*. Although Dutch physics teachers have a vast number of schoolbooks to choose from when teaching this topic, our TLS is the only approach that explicitly takes students' pre-instructional ideas on light propagation as a starting point and that focusses on explaining relativistic phenomena from the basic principles of the theory, the learning aim described in the curriculum document, rather than making calculations.

6.3. Reflections on research reach and scope

Methods of design research, like we used in this study result in learning resources and a local theory that describes if and how the design works. These local theories are humble in the sense that they cannot be generalized over populations per se, but usually they are general enough to be also applicable in other classrooms settings (Bakker, 2018). To get a good grasp of student reasoning and learning, we conducted the first two studies in this project with rather small samples of students. This enabled us to form a thorough understanding of how the design can contribute to student learning.

The pre-instructional reasoning study of Chapter 2, probed 11th grade pre-university level students' ideas on light propagation with the use of EDs. Student reasoning and the representation used to elicit this reasoning are intertwined. This study did not allow us to unravel the reasoning from the tool that allowed students to communicate their ideas. Furthermore, the pre-instructional reasoning study was conducted with 15 students. This limited number means that the presented models may not be exhaustive and that other student models may also be found when studying a larger sample. We have addressed this by using the tasks of this study to activate students' pre-instructional ideas on light propagation in the study of Chapter 5. We noted in Chapter 2 that the tasks did not allow us to distinguish between students reasoning with a constant speed relative to the lamp, or with a constant speed relative to the room. This led us to propose that the student model "constant speed in the lamp-room frame" might disguise two models. Therefore, in Chapter 5, we added a fourth subtask that discriminated between these frames. In that chapter, we presented only whether students used a consistent model, such as described in Chapter 2, or not. However, students' answers to this task indeed included a constant speed to the lamp, the room and the graph paper.

In our view it is not important to know for educators and education designers which of these student models is more common or what percentages can be assigned to each model. For educators, it is important to know that almost all students reason with a consistent pre-instructional model, and that you as a teacher will encounter several of these models when facing a classroom full of students. Therefore, education building on students' pre-instructional ideas should keep all these options in mind.

For the evaluation of the first version of the TLS, we worked with small groups of students. The presented data covered five groups of in total 15 students. This small number allowed us to give very detailed descriptions on possible student learning when working with the TLS. However, this also means that we cannot claim we have presented all the possibilities of student learning with the TLS. We rather showed that, variations in learning paths notwithstanding, the presented design resulted in productive reasoning with the light postulate for all students.

The classroom evaluation of the TLS was done with seven classes. The limitation of this study does therefore not lie with the sample size, but with the scope of the research. To evaluate the TLS, we chose the research design of an evaluative study with many classes. The benefit of this type of study design is that there is some statistical power, and generalizability of learning outcomes over the larger student population. However, we did not address how teacher conduct impacted student learning. Design research strives to answer questions of the format *"What are the characteristics of an <intervention X> for the purpose/outcome Y in context Z?"* (Plomp & Nieveen, 2013a, p. 28). The chosen research design did not include a close study of the context Z, and therefore we cannot explain the outcome Y in much detail. In our overall research design, we assumed that the small-group study, described in Chapter 4, would provide us with enough information on student learning to explain the results of the more coarse-grained approach of the comparative study described in Chapter 5. A case-study focussing on the relation between teacher conduct and student learning could provide valuable additional insights on this aspect.

On top of that, we could question if the instruments used to assess student learning in the two experimental conditions are suitable. We wanted to know if our teaching and learning approach would lead to better conceptual understanding than regular teaching approaches. The Relativity Concept Inventory (RCI, Aslanides & Savage, 2013) seemed a good instrument to assess students' understanding of relativistic concepts without favouring one of the teaching approaches. To provide some additional context, the students were also asked to make two computational tasks and two reasoning tasks. The RCI turned out not to measure an underlying concept for our sample, and as a consequence, the items designed for illustration became the only aspects on which we could compare student learning. Unsurprisingly, the control group scored significantly better on the computational items than the intervention group, probably because they spent more time on this subject matter. All in all, we have shown that our TLS results in fruitful reasoning with the light postulate, but our available data does not provide a complete answer to the question how the relativistic reasoning skills and conceptual understanding of the intervention group compares to that of pupils taught with regular schoolbooks.

6.4. Implications for further research and educational practice

The research presented in this thesis offers fruitful leads for future studies, educational design and educational practice. We presented a teaching and learning approach that gives a conceptual introduction to the light postulate, the relativity of simultaneity and time dilation. However, the Dutch curriculum goal also includes length contraction. As we have remarked in Chapter 1, the relativity principle is not mentioned explicitly in the curriculum goals. Still, it would be worthwhile that secondary students gain an understanding of the principle that fuelled the development of SRT and remains to be an epistemic guideline for new physics theories to come. Therefore, design research studies addressing these concepts could be a good addition to the work we presented in this thesis.

We did design tasks to introduce length contraction as part of the TLS evaluated with small groups. Besides that, a lesson on the relativity principle was designed as part of the classroom TLS. However, these lessons were not part of the two evaluative studies. In the small group-study we wanted to focus our analysis on reasoning with the light postulate. Furthermore, due to time restrictions these lessons were not taught to enough students for a proper evaluation. This also holds for the classroom study, in which teachers did perform all the lesson of the series.

Several studies (Scherr, Shaffer, & Vokos, 2001; Scherr, Shaffer, & Vokos, 2002; Villani & Pacca, 1987) suggested that, to introduce the light postulate and prevent students to stick or fall back to spontaneous light propagation models there should be more attention to Galilean Relativity before SRT is introduced. However, the results of Chapter 2 suggest that students are very flexible in evaluating speeds relative to different reference frames. Similarly, Bandyopadhyay (2009) found that undergraduate physics students have a good understanding of the kinematic aspect of Galilean Relativity. They also found that students do not use the theory-driving aspect of the relativity principle, i.e. the idea that the laws of Mechanics (Galilean Relativity) or all physical laws (Einsteinian Relativity) should remain unchanged under transformation to a different reference frame.

It is this second aspect of the relativity principle that makes it iconic for the theory development of physics. This aspect of the relativity principle can only be properly fathomed by students after they have learned the basic concepts of SRT. Therefore, the relativity principle should not be presented as a rule at the start of SRT-lessons, but should be derived as an overall philosophical principle at the end. I will illustrate this with an example from my own teaching practice. When I used one of the regular approaches teaching SRT, I asked my students the following question in the first lesson: *Imagine that we are in a laboratory and that we have all equipment to conduct whatever experiment we can come up with. At a certain point we all fall asleep, and when we wake up, it appears that we cannot leave the lab or communicate with the outside world. Our first priority is to find out if we are not abducted by aliens and are now well on our way to a distant galaxy. Can you think of an experiment that would tell us where we are or how fast we are going?* One of the students, Frederik, proposed to drill a small hole in the wall of the lab, so light from outside could come in, and we could measure its speed. This student argued that if he would measure “the” speed of light, this would tell us that we were not moving. However, If he would find a higher or lower speed, we were moving towards or away from the sun. This reasoning is flawless considering that the student is reasoning with a pre-instructional light propagation model. To point out why this reasoning is nonetheless incorrect, I as a teacher, needed to refer to concepts that were not yet introduced to the students. When the light postulate, time dilation and length contraction are introduced, students have the conceptual tools to find out that there is no experiment that could provide an answer to these questions, and that indeed the laws of nature are unchanged under transformation.

Special Relativity Theory combined space and time intro one unified spacetime and transformed the way physicists look at the world. By introducing SRT to secondary students we ask them to rethink the way they look at the world as well. When they do this, students learn new, exciting, and counterintuitive concepts that can be motivating for learning physics. However, rethinking how you look at the world can also make you feel lost or cheated by what you have learned thus far. In short, learning SRT does not only have a cognitive aspect but also an emotional one. The scope of our research was limited to students conceptual learning. Addressing these affective variables and studying how they impact student learning may be a valuable addition to the knowledge base on teaching and learning SRT.

Another topic for future research would be the teacher perspective on SRT. In the previous section of this discussion we already suggested that the interaction between teacher conduct and student learning was a missing perspective in our study. Besides that, there is the broader issue of the conceptual recourses teachers need for guiding students in learning SRT. The research literature on SRT learning is limited, the teacher perspective however, is virtually non-existent. The one study we are aware of that includes both in-service teachers and Special Relativity, addresses how physics teachers approach innovation[2] (De Ambrosis & Levrini, 2010). Nonetheless, the image gained from the general research literature is that learning SRT is difficult for all types of students, be it secondary students, pre-service teachers or science students. There is no reason to assume why in-service teachers should be the exception to this rule, and therefore it would be interesting to pursuit the venture of how teachers can be further supported to teach SRT.

A more general venture for future research is to further explore the possibilities of styles of scientific reasoning as an instructional approach. In this research project we drew on hypothetical modelling, one of these reasoning styles, as a way to introduce the light postulate and derive relativistic concepts while students engaged in the characteristic style of reasoning portrayed in SRT. This approach was inspired by the work of Kind and Osborne, who proposed

[2] Although this attitude is a force to be reckoned with when introducing a new curriculum, given the heated discussions in the physics education community between those in favour of new physics (NiNa), and learnable physics (LeNa) (Lijnse, 2007).

styles of scientific reasoning as a cultural framework to design and organize science curricula (2017). In this paper, the authors explain that the natural sciences draw on six different styles of reasoning, rather than just one scientific method. These styles of reasoning are mathematical deduction, experimental evaluation, hypothetical modelling, categorization and classification, probabilistic reasoning, and historical-based evolutionary reasoning. Osborne, Rafanelli and Kind (2018) argue that these styles of reasoning are a better way to organize the US K-12 curriculum than the idea of crosscutting concepts that are currently used.

When physicists engage in hypothetical modelling, they propose a new model that intends to explain the phenomena at hand better than the previous theory. In the context of education, students' pre-instructional ideas and experiences take on the role of this previous theory. In this dissertation we have shown that engaging in hypothetical modelling activities with pre-instructional models of light propagation is beneficial for students to come to reason with the light postulate, derive relativistic concepts and be convinced of those concepts. However, we did not make it explicit to students that they engaged in a specific style of reasoning or that this reasoning style is prototypical for theory development in physics. For future research, it would be worth pursuing if additional reflection on the overall approach used in solving the tasks, can contribute to students' Scientific Literacy. Furthermore, it would be interesting to see if styles of reasoning as an instructional approach is fruitful for other styles of reasoning as well. This way, styles of scientific reasoning may not only be a way to organize a curriculum, but serve also as a means to familiarize students with this aspect of scientific practice.

6.5. Reflections on the research context

I performed this research project as a teacher-researcher in the context of the Promodoc grant for teachers at the start of their career. This means I worked both as a researcher and a physics teacher. This dual identity and practical context has influenced how we conducted the research. It is therefore important to describe this context and how it impacted both teaching and research practice.

The past years, I conducted this PhD-research next to working as a physics teacher at the Gemeentelijk Gymnasium Hilversum, a school for pre-university level secondary education. The combination of two jobs that both tend to demand more than the available time, has been challenging. Especially in the first years when my teaching schedule ensured maximum variation, each day working at a different place than the day before and rushing back to Utrecht after morning classes to conduct research, two days a week. Due to this context, we made some choices in the research design motivated by time constraints. For instance, not to observe the lessons in the classroom study of Chapter 5 in person. Planning the research in the available time is a concern that is not unique for teacher researchers, but may be more prominent in the context of teacher-researchers.

Nevertheless, the dual role of being both a teacher and a researcher has benefitted this research as well. The main benefit was that I had a profound knowledge of the context in which the TLS eventually had to function. Because of this, smaller decisions concerning general pedagogy were easy to make and we could keep an eye on the ball, so to speak.

Teaching is not just about transferring subject knowledge; it is primarily about connecting with students. It is this pedagogical context, that is conditional for learning. It was advantageous that I could draw on my teaching experience when conducting the small group study of Chapter 4. This ensured that the TLS was performed well from a teaching perspective. From a research perspective, it ensured that the TLS was performed in the intended fashion, and we did not have to deal with transfer issues for this first proof of principle of the educational design.

Teachers and researchers have different quality concerns for education research. For instance, teachers are inclined to dismiss or oppose research findings when they conflict with their own experiences (Groothuijsen, Bronkhorst, Prins, & Kuiper, 2020). This is a factor of significance when involving teachers in design research in a way that is fruitful both for the teachers themselves and for the research. My teaching experience, knowing first-hand what teachers look for in research, helped to involve teachers as co-designers in the study of Chapter 5. As a result, there arose a sense of ownership and personal involvement with these teachers. This contributed not only to a truthful implementation. The teachers also showed me a lot of patience and consideration when I did not directly succeed in conveying my ideas clearly.

Finally, the double role of teacher-researcher did not only influence the research, it also impacted my view on education. The opportunity to create and conduct this research project, nourished and renewed my perspective on teaching and learning and my teaching practice. It inspired me to rethink what I wanted to achieve with my students, not only for the topic of Special Relativity, but for other topics as well. My focus shifted from teaching concepts, equations and conducting experiments, to reasoning with these concepts and basic principles at a level appropriate for students' understanding at that time. The execution and implementation of these type of teaching activities were surpassed by my interest, because of the previously mentioned time constrains. Nonetheless, it is a good resolution to take with me to the future.

Overview of publications related to this thesis

Kamphorst, F., Vollebregt, M. J., Savelsbergh, E. R., & van Joolingen, W. R. (2019). Students' pre-instructional reasoning with the speed of light in relativistic situations. *Physical Review Physics Education Research*, *15*(2), [020123]. https://doi.org/10.1103/PhysRevPhysEducRes.15.020123

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Kamphorst, F., Savelsbergh, E., & Vollebregt, M. J. (2019). Wat betekent lichtsnelheid voor leerlingen? *Nederlands Tijdschrift voor Natuurkunde, 85*(12), 14–17.

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Kamphorst, F., Vollebregt, M.J., Savelsbergh, E.R., van Joolingen, W.R. (2021b) An educational reconstruction of special relativity theory for secondary education. *Science & Education*, 1–44. https://doi-org.proxy.library.uu.nl/10.1007/s11191-021-00283-2

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Kamphorst, F. (2016). *Special relativity theory in Secondary Education – guided reasoning with propagation of light and reference frame.* Poster session presented at ESERA Summer School 2016, České Budějovice, Czech Republic, August 22-26.

Kamphorst, F. (2016-2017). *Relativiteit in de klas*. U-Talent teacher professionalization course, Utrecht, the Netherlands, October 26, November 11, January 25, April 12 and May 10.

Kamphorst, F., Vollebregt, M. J., Savelsbergh, E. R., & van Joolingen, W. R. (2017). *A constant speed of light: what does it mean to students in secondary education?* Poster session presented at ESERA 2017, Dublin, Ireland, August 21-25.

Kamphorst, F. (2018). *Professional Learning Communinity – Relativiteit in de klas I.* U-talent teacher professionalization course, Utrecht, the Netherlands, January 18, 25, February 8, 11, June 8.

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Kamphorst, F., Savelsbergh, E. R., Vollebregt, M. J., & van Joolingen, W. R. (2018). *A meaningful introduction to the light postulate for secondary education students*. Presentation at GIREP-MPTL, San Sebastian, Spain, July 9-13.

Kamphorst, F. (2018). *Speciale Relativiteit – Leerlingen ondersteunen bij redeneren.* Workshop at Werkgroep Natuurkunde Didactiek Conferentie *Energie in Transitie*, Noordwijkerhout, the Netherlands, December 14-15.

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Relativiteit in de klas – samenvatting in het Nederlands

Vol spanning keken we uit naar het college op vrijdag tijdens mijn eerste week op de universiteit. Na alle introductie-activiteiten en colleges in wiskunde en modelleren, ging het nu eindelijk gebeuren: Een natuurkundecollege. Met een opgewekt “as is easy to see” toverde de docent de ene na de andere onbegrijpelijke formule op het bord. Dit was mijn eerste kennismaking met Speciale Relativiteitstheorie (SRT). Jammer genoeg droeg de nadruk op het wiskundig formalisme voor mij weinig bij aan het gaan begrijpen van de theorie en de relativistische concepten. Het bleef een individuele zoektocht om betekenis te verlenen aan waar relativiteit allemaal over ging.

Deze zoektocht begon twee jaar eerder in de uren na de laatste natuurkundeles van de week. Met een klein groepje bleven we in het lokaal hangen om ons begrip van het leven, het universum en alles verder te ontwikkelen. Daarbij hadden we het vaak over natuurkunde die ons fascineerde, zoals de relativiteitstheorie. Onze fascinatie was niet misplaatst. Speciale relativiteit is een van de iconische natuurkundetheorieën en een schoolvoorbeeld van hoe kennis in dit veld tot stand komt. Daarom is het wenselijk dat middelbare schoolleerlingen kennismaken met deze theorie.

SRT deed zijn intrede in het Nederlandse VWO curriculum in 2013 als keuzeonderwerp. Deze introductie was onderdeel van een grote curriculumvernieuwing. Een van de doelen van deze curriculumvernieuwing was dat leerlingen het verband tussen de grote ontdekkingen in de natuur- en sterrenkunde en maatschappelijke ontwikkelingen konden ervaren. Een ander doel was dat leerlingen kennis konden maken met de wetenschappelijke manier van denken als een menselijke activiteit en de bijdrage van deze denkwijze aan onze samenleving (Commissie Vernieuwing Natuurkundeonderwijs, 2006).

Toen ik begon als natuurkundedocent, was de natuurkunde-onderwijsgemeenschap volop in voorbereiding voor dit nieuwe curriculum. Samen met mijn collega’s worstelde ik met de vraag hoe we les moesten geven in alle nieuwe curriculumonderwerpen. Voor onze leerlingen leek de wiskundige benadering uit dat eerste natuurkundecollege nog minder op zijn plaats. Niet alle leerlingen hebben de vaardigheden om natuurkunde te gaan begrijpen aan de hand van die benadering. Tijdens de nascholingen die ik volgde om me op dit nieuwe onderwijs voor te bereiden, kwam juist die wiskundige benadering steeds weer terug. Daarmee bleef mijn grote vraag onbeantwoord: Wat kan ik doen in de les, om leerlingen iets te laten begrijpen van relativiteit?

Dit verlangen, om mijn vaardigheden in het onderwijzen van relativiteit te verbeteren en uit te breiden, inspireerde de totstandkoming van dit onderzoeksproject. Dat we ons zo verloren voelde in hoe we relativiteit moesten onderwijzen, kan deels worden toegeschreven aan de beperkte onderzoeksliteratuur over dit onderwerp (zie bijvoorbeeld Dimitriadi & Halkia, 2012; Dimitriadi & Halkia, 2010; Levrini & DiSessa, 2008; Scherr, Shaffer, & Vokos, 2001; Scherr, Shaffer, & Vokos, 2002). Volgens een recente overzichtsstudie (Alstein, Krijtenburg-Lewerissa & van Joolingen, 2021) is het moeilijk om relativistische concepten te gaan begrijpen en geven die moeilijkheden aanleiding voor hardnekkige misconcepten. Daarom moet onderwijsontwerp voor relativiteit in het voortgezet onderwijs expliciet rekening houden met deze leermoeilijkheden.

Dit onderzoek heeft tot doel bij te dragen aan de wetenschappelijke kennisbasis voor relativiteitsonderwijs in het voortgezet onderwijs door het ontwerp en de evaluatie van een onderwijsleertraject. Daartoe hebben we een hulpmiddel ontwikkeld, het gebeurtenisdiagram dat leerlingen ondersteunt bij het uitvoeren van relativistische gedachte-experimenten (**Hoofdstuk 2**). We hebben dit hulpmiddel ook aangewend om het redeneren van leerlingen met lichtvoortplanting voorafgaand aan onderwijs over het lichtpostulaat te onderzoeken (**Hoofdstuk 3**). Deze inspanningen vormden het vertrekpunt voor de didactische reconstructie van SRT, gericht op het introduceren van het lichtpostulaat bij leerlingen van de bovenbouw van het VWO (**Hoofdstuk 4**). De taken in het onderwijsleertraject zijn gebaseerd op relativistische gedachte-experimenten ondersteund door gebeurtenisdiagrammen. Het ontworpen onderwijsleertraject is getest in een kleinschalig onderwijsexperiment. De laatste studie richt zich op het opschalen voor en testen in de klassencontext van het onderwijsontwerp (**Hoofdstuk 5**).

Gedachte-experimenten zelf uitvoeren met behulp van gebeurtenisdiagrammen

In **Hoofdstuk 2** introduceren we een visuele representatie die middelbare schoolleerlingen ondersteunt in relativistisch redeneren: Het gebeurtenis-diagram[1] (GD). Een voorloper van het GD was eerder voorgesteld door Scherr (2001), en we hebben dit ontwerp aangepast om gedachte-experimenten[2] (GEs) mee uit te kunnen voeren. Daarnaast presenteerden we drie voorbeelden waarin relativistische GEs worden ondersteund met GDs.

[1] Event Diagram of ED in het Engels.
[2] Thought Experiment of TE in het Engels.

Er zijn diverse redenen die het voor leerlingen moeilijk maken om GEs zelf uit te voeren. Ten eerste verhult de wijze waarop GEs vaak worden gepresenteerd het redeneren dat leidt tot de uitkomst en overkoepelende conclusie van het GE. Ten tweede moeten leerlingen redeneren met een absolute lichtsnelheid om GEs uit te voeren, iets dat verschrikkelijk lastig is voor leerlingen en studenten op alle onderwijsniveaus (Gousopoulos, Kapotis, & Kalkanis, 2016; Villani & Pacca, 1987). Ten derde moeten leerlingen bij het uitvoeren van een relativistisch GE, gebeurtenissen interpreteren ten opzichte van twee referentiekaders die ten opzichte van elkaar bewegen. Hiervoor moeten leerlingen in gedachte twee sporen tegelijk bewandelen: Relatieve beweging tussen de referentiekaders en redeneren met tegenintuïtieve concepten. Wij hebben voorgesteld dat een externe representatie van ruimtetijd in de vorm van een GD, leerlingen kan ondersteunen tijdens het zelf uitvoeren van relativistische GEs.

GDs zijn representaties van ruimtetijd die in plaatjes de plaats van objecten en gebeurtenissen tonen voor opeenvolgende tijdstippen, vanuit een specifiek referentiekader. Scherrs versie van de GD biedt een visuele organisatie van de informatie gegeven in opgaven, maar geeft geen expliciete ondersteuning voor het redeneren van leerlingen over lichtvoortplanting. Om dit aspect te adresseren, hebben we drie eigenschappen toegevoegd aan onze GDs. We hebben de GD op ruitjespapier getekend en we hebben meerdere plaatjes aan de GD toegevoegd. Het eindresultaat is dat in het GD, de positie van objecten en gebeurtenissen tijdens opeenvolgende tijdstippen afgebeeld wordt. Hierdoor is het mogelijk om op basis van de GD snelheden aan objecten toe te kennen en de positie van lichtflitsen in de GD te tekenen. Daarmee wordt het relativistische redeneren tijdens het uitvoeren van GEs ondersteund. Tot slot hebben we de uitkomst van het GE juist niet laten zien in de GD. Leerlingen moeten zo echt een redenering opbouwen om de uitkomst van de GE af te leiden.

Een belangrijke bijdrage voor het onderwijs is dat we de stappen van het uitvoeren van een GE hebben geïntegreerd in ons taakontwerp. De eerste stap van het uitvoeren van een GE bestaat uit het beschrijven van de beginsituatie, het definiëren van je theoretisch kader en het formuleren van de centrale vraag, die je graag met je GE wilt beantwoorden. In ons taakontwerp wordt de beginsituatie afgebeeld in de GD en de centrale vraag gepresenteerd in de taak zelf. Leerlingen kunnen zelf een theoretisch kader kiezen om de GE uit te voeren, of hun docent kan opdracht geven een specifiek kader te gebruiken. In de tweede stap wordt de centrale vraag beantwoord door middel van een afleiding met dat theoretisch kader, die vanuit de beginsituatie tot de uitkomst van de GE leidt. In onze taak, redeneert de leerling tijdens dit proces door de positie van lichtflitsen in opeenvolgende plaatjes van het GD te tekenen. Hierdoor bepaalt de leerling de positie en het tijdstip van gebeurtenissen. De derde en laatste stap van een GE beslaat het trekken van een algemene conclusie, gebaseerd op de uitkomst. In gesprek met de docent geven leerlingen, in ons taakontwerp, betekenis aan de uitkomst van het GE in een overkoepelende reflectie.

Spontaan redeneren met lichtvoortplanting

Het doel van de studie die in **Hoofdstuk 3** wordt beschreven is om de onderliggende modellen bloot te leggen die leerlingen gebruiken als ze met lichtvoortplanting redeneren. Om dit te onderzoeken, hebben we een klinische interviewstudie uitgevoerd, waarin 15 5-VWO leerlingen (16-18 jaar) werd gevraagd om een redeneertaak uit te voeren waarbij ze licht in GDs tekenden. De leerlingen maakten in totaal zes van dit soort taken. Drie verschillende versies van een niet-relativistische taak, en drie versies van een relativistische taak waarin de waarnemer en de lichtbron ten opzichte van elkaar bewogen.

De leerlingen in ons onderzoek maakten hun redeneren expliciet en gebruikten daarbij GDs om de uitkomst van de taken af te leiden door stapsgewijs te redeneren met lichtvoortplanting. Leerlingen gebruikten de volgende procedure: Ze bepaalden de afstand die licht sinds het vorige tijdstapje afgelegd had en gebruikten deze afstand om de positie van de lichtflits te bepalen op het volgende tijdstip. Nadat de leerlingen waren geïnstrueerd over hoe ze GDs konden gebruiken om te redeneren met lichtvoortplanting door middel van tekenen, gebruikten 14 van de 15 leerlingen de GDs ook daadwerkelijk om de redeneertaken uit te voeren. Deze resultaten leidden tot de conclusie dat leerlingen GDs als productief redeneerhulpmiddel kunnen gebruiken.

Leerlingen maakten gebruik van verschillende licht-voortplantingsmodellen om de relativistische taken op te lossen. Een deel van de leerlingen redeneerde met een constante lichtsnelheid ten opzichte van het ruitjespapierreferentiekader. Andere leerlingen redeneerden met een constante lichtsnelheid ten opzichte van het referentiekader van de lamp en de kamer. Leerlingen die redeneerden met een constante lichtsnelheid ten opzichte van het ruitjespapier richtten zich op de beweging van object, terwijl leerlingen die redeneerden met een constante lichtsnelheid ten opzichte van de lamp en kamer zich voornamelijk bezighielden met de positie van objecten.

Ongeacht het specifieke voortplantingsmodel waarmee de leerlingen de taken uitvoerden waren zij flexibel in het aflezen van de lichtsnelheid ten opzichte van andere referentiekaders. Natuurkundigen zouden met het lichtpostulaat steeds dezelfde waarde vinden voor de lichtsnelheid wanneer ze dit zouden doen. Leerlingen niet. Die vinden verschillende snelheden. Ondertussen zeggen leerlingen, net als natuurkundigen, dat alle waarnemers het eens zijn over de lichtsnelheid. Ze bedoelen daar alleen iets heel anders mee dan natuurkundigen. Ze bedoelen dat alle waarnemers het eens zijn over het referentiekader (bijvoorbeeld dat van de kamer en de lamp) ten opzichte waarvan licht zijn eindige snelheid heeft. In ons welwillend toehoren van de leerling, moeten we er dus op bedacht zijn dat we bij dit soort uitspraken niet gelijk denken dat leerlingen het lichtpostulaat hebben begrepen.

Een belangrijk resultaat van deze studie is dat een aantal leerlingen van referentiekader voor constante lichtsnelheid wisselden terwijl ze de taken uitvoerden. Sommige van deze leerlingen werden zich bewust van het andere referentiekader, en gaven aan dit nieuwe kader de voorkeur boven het referentiekader waarmee ze de taak waren begonnen. Anderen ontdekten een conflict tussen het idee van lichtsnelheid als maximum snelheid in het universum en hun eigen model. Dit resultaat is van belang voor het onderwijs omdat we daar ook tot doel hebben om het redeneren van leerlingen te veranderen, zij het in dat geval van een spontaan model naar het lichtpostulaat. Het expliciet problematiseren van referentiekaders voor lichtvoortplanting zou weleens een interessante aanpak kunnen zijn om het lichtpostulaat te introduceren.

Didactische Reconstructie van Speciale Relativiteitstheorie voor het middelbaar onderwijs

In **Hoofdstuk 4** beschrijven we het ontwerp en de evaluatie van een onderwijsleertraject waarbij we voortbouwen op het eerdergenoemde conflict tussen verschillende spontane lichtvoortplantingsmodellen. In dit hoofdstuk stellen we dat SRT een uitstekend onderwerp is om leerlingen kennis te laten maken met het proces van wetenschappelijke kennisontwikkeling. Tegelijk zou relativiteitsonderwijs voort moeten bouwen op leerlingideeën, zodat het onderwijs ze helpt om de kloof te overbruggen tussen hun spontane ideeën en de natuurkundige begrippen. Om in ons onderwijsontwerp aan beide doelen te voldoen, hebben we een didactische reconstructie van SRT voor het voortgezet onderwijs uitgevoerd. Dit geleidt tot een conceptuele structuur voor een onderwijsaanpak, die vervolgens omgezet is in een onderwijsleertraject dat als hypothetisch leertraject (HLT) is gepresenteerd.

In het eerste deel van Hoofdstuk 4 presenteren we de didactische reconstructie en het hypothetisch leertraject (HLT). We hebben SRT geanalyseerd door de lens van het Nederlandse curriculumdoel en de visie van Lakatos aangaande wetenschappelijke onderzoeksprogramma's. Uit deze analyse kwam naar voren dat het overkoepelende doel van SRT was om het klassieke relativiteitsprincipe van Galilei dat stelt dat de wetten van mechanica onveranderd blijven onder transformatie tussen inertiaalstelsels, uit te breiden naar de domeinen van optica en elektromagnetisme. Daarmee wordt een schijnbare asymmetrie in Maxwell's elektromagnetisme opgelost. Het redeneren in SRT kan getypeerd worden als hypothetisch modelleren, waarbij relativistische fenomenen worden afgeleid van een aantal basale concepten zoals gebeurtenissen en referentiekaders met behulp van het lichtpostulaat. Het relativiteitsprincipe functioneert daarin als epistemische leidraad die voorschrijft waar het eindproduct aan moet voldoen. We wilden deze redeneerstijl graag behouden in ons onderwijsontwerp, maar achtten de schijnbare asymmetrie in de interpretatie van elektromagnetisme ongeschikt voor leerlingen.

Het overkoepelende leerdoel van ons onderwijsontwerp is dat de lessen bij leerlingen zou moeten leiden tot productief redeneren met het lichtpostulaat. Dit hebben we gedefinieerd als het lichtpostulaat kunnen gebruiken om relativistische fenomenen af te leiden. We stellen dat de volgende inzichten bij kunnen dragen om leerlingen te laten ervaren dat ze met een ander dan hun spontane lichtvoortplantingsmodel moeten gaan redeneren:

1. Lichtvoortplanting is altijd ten opzichte van een referentiekader,
2. Er zijn verschillende mogelijkheden voor dit referentiekader,
3. Voorspellingen met lichtvoortplanting hangen af van de keuze voor dit referentiekader, en
4. Hun huidige redeneren leidt tot verkeerde of inconsistente voorspellingen.

Om vervolgens ook daadwerkelijk het lichtpostulaat te gaan gebruiken en daar productief mee te redeneren, is het nodig dat leerlingen:

5. Hun referentiekader voor lichtvoortplanting veranderen naar het referentiekader van de waarnemer,

6. Ervaren dat dit nieuwe lichtvoortplantingsmodel het probleem oplost met hun spontane model, en
7. De gevolgen van dit nieuwe model verkennen.

Deze twee fasen van theorieontwikkeling (1-4 en 5-7) komen aan de orde in de twee delen van ons onderwijsontwerp, en illustreren hoe de belangrijkste ideeën en theorieontwikkeling van SRT kunnen worden gereconstrueerd in een inhoudsstructuur voor een onderwijsaanpak. De taken die deel uitmaken van het onderwijsleertraject nodigen leerlingen uit tot hypothetisch modelleren met hun spontane lichtvoortplantingsmodel en het lichtpostulaat.

In de evaluatie van het onderwijsleertraject hebben we aangetoond dat het ontwerp leerlingen in staat stelt om een conceptueel begrip van SRT te ontwikkelen, met name van het lichtpostulaat. Van de 15 leerlingen waren 13 overtuigd van het lichtpostulaat als een voortplantingsmodel. Alle leerlingen gebruikten het lichtpostulaat om andere relativistische fenomenen af te leiden en interpreteerden daarbij snelheid, het tijdstip van een gebeurtenis en tijdsduur ten opzichte van een specifiek referentiekader. Tijdens de lessen hebben de leerlingen hypothetische modelleer-activiteiten uitgevoerd waarin ze redeneerden met hun spontane lichtvoortplantingsmodel en het lichtpostulaat. Daarmee hebben we aangetoond dat een onderwijsleertraject gebaseerd op hypothetisch modelleren met spontane licht-voortplantingsmodellen leerlingen mee kan nemen in de theorieontwikkeling van SRT.

Introductie van het lichtpostulaat in de klas

Het onderwijsleertraject beschreven in Hoofdstuk 4 is verder ontwikkeld om in de klas te worden gebruikt. De aanpassingen aan het onderwijsontwerp en de evaluatie van deze versie van het onderwijsleertraject zijn beschreven in **Hoofdstuk 5**.

Het opschalen van het onderwijsontwerp voor deze nieuwe klassencontext[3] is gedaan in nauwe samenwerking met een groep natuurkundedocenten, die ook betrokken waren bij het implementeren van het onderwijsontwerp in hun eigen lespraktijk. In deze versie hebben we de redeneertaken waarin leerlingen gedachte-experimenten uitvoeren opgedeeld in twee afzonderlijke taken: Een redeneertaak en een reflectietaak. De analyse van leerlingantwoorden op vijf van deze taken toont aan dat het

[3] Het lesmateriaal is gepubliceerd op https://www.fisme.science.uu.nl/toepassingen/28984/

onderwijsleertraject voor een meerderheid van de leerlingen leidt tot productief redeneren met het lichtpostulaat in deze klassencontext. De vergelijking van leerlingenantwoorden op twee GEs, een versie ondersteund met een GD, en een versie die als open vraag zonder externe representatie is gepresenteerd, suggereert dat ons taakontwerp leerlingen ondersteunt bij het uitvoeren van relativistische gedachte-experimenten in de klassencontext.

Deze studie is een eerste aanzet om ons onderwijsontwerp toe te passen in de klas. Deze eerste uitvoering leidde tot een gelijk niveau in het uitvoeren van redeneertaken voor leerlingen die les hebben gehad met onze methode en leerlingen die onderwezen zijn aan de hand van een reguliere lesmethode. Extra aandacht voor hoe het handelen van de docent en de aard van het onderwijsleergesprek bijdraagt aan leren, zou dit resultaat zelfs nog verder kunnen verbeteren.

Tot slot

Dit onderzoek is opgezet vanuit de wens bij te dragen aan de onderwijspraktijk voor SRT in het voortgezet onderwijs door de wetenschappelijke kennisbasis over dit onderwerp te vergroten. We hebben laten zien wat voor soort taken kunnen bijdragen aan begripsopbouw van relativistische concepten. Daarnaast hebben we een hulpmiddel ontwikkeld, het gebeurtenisdiagram, dat het redeneren met lichtvoortplanting expliciet maakt en dat leerlingen ondersteund bij het uitvoeren van relativistische gedachte-experimenten. Onze voornaamste bijdrage is het onderwijsleertraject dat we in het kader van dit onderzoek hebben ontwikkeld, waarin het lichtpostulaat conceptueel geïntroduceerd wordt.

Terugblik

De ontdekkingsreis die heeft geleid tot het behalen van mijn doctorstitel begon in het voorjaar van 2015. Tijdens een veel te lange rapportvergadering in een veel te warm en vol lokaal kreeg ik een email van Gjalt of ik een voorstel voor een promotieonderzoek wilde schrijven. Een paar maanden daarvoor had ik laten vallen dat me het wel wat leek om promotieonderzoek te doen als ik een nieuwe uitdaging nodig zou hebben naast het lesgeven. Deze gelegenheid kwam vele jaren eerder op mijn pad dan ik verwacht had. Toch ben ik op weg gegaan naar de Uithof voor een eerste kennismakingsgesprek. Tijdens dat gesprek met Gjalt en Elwin laaide het vuur van enthousiasme zo hoog op dat ik begon aan de schier onmogelijke taak om binnen een maand een onderzoeksvoorstel te schrijven. Ik dank jullie en Marjolein dat jullie tijdens die opstartfase iets in mij hebben gezien dat ik toen zelf nog niet scherp zag.

Wanneer we terugkijken en vertellen over hoe gebeurtenissen en omstandigheden hebben geleid tot waar we vandaag staan, zijn we vaak geneigd om een beginpunt te kiezen en vanuit daar een min of meer rechte weg te schetsen naar het eindpunt. Op landkaarten betekenen rechte wegen één van twee dingen: een weg door de polder, of de kaart heeft een grote schaal. Iedereen die weleens door de polder is gefietst weet dat je je dan mag verheugen op kilometers ploeteren met tegenwind, vaak ook nog met regen. De kaarten op grote schaal verliezen elk detail waardoor bochten, bergen en obstakels die we onderweg tegenkomen verborgen blijven.

Ook deze terugblik versluiert onvermijdelijk de obstakels en kuilen in de weg die ik tijdens het uitvoeren van mijn onderzoek tegen ben gekomen. Op deze moeilijke momenten heb ik me gelukkig mogen prijzen met velen die mij tot steun zijn geweest. Elwin en Marjolein, dank jullie wel dat jullie er waren, juist op de momenten dat het er echt toe deed. Mirjam en Jan Luiten, jullie luisterend oor, scherpe blik en wijze raad hebben veel voor mij betekend. Alle mooie momenten kregen extra glans dankzij alle steun, belangstelling en gezelligheid die ik samen met mijn collega's op het FI en het GGH heb mogen ervaren.

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Curriculum Vitae

Floor Kamphorst was born 4 August 1986 in Nieuwegein, the Netherlands. She obtained her pre-university level secondary degree (VWO) at the Montessori Lyceum Herman Jordan in Zeist in 2005. She then proceeded to study Physics and Astronomy at Utrecht University. In 2009, she spent a gap year as a board member and treasurer for the Utrecht Student Choir and Orchestra (USKO). In 2011, she obtained her bachelor's degree, with a research project titled *Crystallization and manipulation of colloids by dielectrophoresis and a template*. She then proceeded with her Masters in Science Education and Communication. As part of this masters programme, she performed a research project titled *Transmission through a nano hole grating* and obtained her teaching degree.

Since September 2011 she has been working at the Gemeentelijk Gymnasium Hilversum as a physics teacher. In 2015, she started her PhD research project on teaching relativity theory in secondary schools. For this project, she was rewarded the Promodoc Grant of the Ministry of Culture, Science and Education (OCW) for teacher researchers. After obtaining her PhD, Floor will start working at the Norwegian University of Science and Technology (NTNU) in Trondheim as Associate Professor in Science Education.

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Special relativity theory (SRT) is an iconic physics theory and prototypical for how new knowledge develops in this field. Therefore, learning SRT can be valuable for secondary school students. SRT was introduced in the Dutch pre-university level secondary physics curriculum (VWO) as an elective topic in 2013. However, learning relativistic concepts gives rise to some robust misconceptions and little is known on how to teach this topic at the secondary level. This research project aims to contribute to the scientific knowledge base of learning SRT in secondary physics education through the design and evaluation of a teaching and learning sequence (TLS).

The first study deals with students' pre-instructional reasoning on the light postulate, which states that the speed of light is the same regardless of the state of motion of its source or the observer. We developed a reasoning tool, the Event Diagram, that supports secondary students to perform relativistic thought experiments. We found that students used one of two different models for light propagation. Some of them switched models when they experienced a mismatch between different reference frames. The second study presents an educational reconstruction of SRT, yielding a TLS introducing the light postulate by presenting such a mismatch. Evaluation in small groups showed students developed confidence in the light postulate and used it to derive relativistic concepts. In the final study, the TLS was adapted for the classroom and evaluated in seven classes. Also in this context, the TLS resulted in productive reasoning with the light postulate.