Evaluating key ideas for teaching electromagnetic radiation

Sarah ZLOKLIKOVITS and Martin HOPF
University of Vienna, Austria

Abstract. Although electromagnetic radiation is an omnipresent phenomenon in our everyday life, in Austria it is only taught in high schools. Our aim is to develop a research-based teaching and learning sequence on electromagnetic radiation for the middle school level. As a first design step, we developed central explanations, so called key ideas, to introduce the term of electromagnetic radiation and the interaction with matter. Those key ideas were evaluated with teaching experiments, using the method of probing acceptance. The outcomes are encouraging and help us to get a better understanding of students’ problems and their perspectives while learning about radiation. The key ideas were adapted accordingly.

1. Introduction
Electromagnetic radiation plays a crucial role in our everyday life - from being exposed to the sun, sending a tweet, to getting an X-ray at the dentist. At the same time, studies show that even high school students often know very little about electromagnetic radiation and hold many misconceptions (see 2.2).

Electromagnetic radiation is not part of the mandatory education in Austria. Given the importance of the topic and the lack of knowledge attested by research, we claim that implementing the topic into middle school education would be beneficial. For this reason, we are developing a teaching-learning-sequence (TLS) to introduce the topic to 14-year old students. Working under the paradigm of design research, we developed a prototype of the TLS based upon existing research. This first prototype of the TLS covers the whole electromagnetic spectrum, nonvisible radiation as well as visible radiation. In this paper, we present the outline of the TLS as well as the results of the first empirical, qualitative studies of the implementation.

2. Theoretical Background

2.1. Design research
It is often complained that results from educational research do not find their way into the classroom. One strategy to overcome that problem is Design research. Design research “combines instructional design and educational research” [1]. Using this approach, the development of an instructional design goes hand in hand with constant implementation and evaluation. Alongside creating an evidence based and practical design, this research approach aims to gain domain specific educational knowledge [2]. During the first research cycles researchers often work with single students in laboratory settings, then they move on to implementing the design in “real” classrooms, leading up to bigger studies with quantitative evaluations [3]. The aim of the first circles of design research is to establish “humble theories” – pragmatic insights into topic-specific learning processes that help to refine the design [1]. The presented work represents research in the very first circle of a design research project. In order to implement a complex topic like electromagnetic radiation in the first years of physics education, a lot of thought must go into the way the content is structured, considering students’ capabilities and perspectives [4]. A model that incorporates those considerations into the design process
and substantially influenced the presented work is the model of educational reconstruction (MER) [5]. Following this model, the development of a design goes hand in hand with clarifying the scientific content considering research on teaching and learning. The model describes designing as an iterative process, as the evaluation of the design feeds back to the structuring of the science content and educational research. The model agrees very well with design research, as the two frameworks share their cyclic nature and the constant refinement of both the design and the underlying theory. MER encourages researchers to rethink the way a scientific content is traditionally taught, often leading to instructions that differ from typical physics textbooks.

2.2. Findings from Physics Education Research

Only few studies have been done on the learning and teaching of electromagnetic radiation. But as it seems, students’ knowledge is fragmentary. For example, students do not know the difference between ionizing and non-ionizing radiation [6]. They tend to distinguish between “good” and “bad” radiation [4], “natural” and “unnatural” as well as “harmless” and “dangerous” radiation [7, 8]. Studies indicate that students lack knowledge regarding health-related issues as well, for example the potential risk of UV exposure and the appropriate protective measures [9, 10].

More is known about the teaching of optics. A curriculum on geometrical optics for middle school that has already been proven to foster students’ learning was developed by Haagen-Schützenhöfer [11]. Traditional optics courses use the ray model to explain optical phenomena, however, this model does not foster conceptual learning [12]. In Haagen-Schützenhöfers model, instead of using ray diagrams, the propagation of light is represented by “cone shaped beams” that have an arrowlike form. Another key element of this optics curriculum is the sender-receiver model: all processes are followed from the source of the light to the receiver.

3. The first prototype of the TLS

We will now outline the learning path of the first prototype of our TLS and highlight some of the considerations that led to the formulation of the central explanations that build the foundation of the TLS, the so called key ideas. The exact phrasing of the key ideas can be found in table 1. It must be stressed that the formulation of the key ideas was driven by MER.

3.1. Explaining electromagnetic radiation without particles or waves

As the focus of this paper is set on the first evaluation, we cannot go into much detail about the lengthy process that led to the key ideas presented in this paper. This process led us to reconstruct the topic of electromagnetic radiation in a way that you will not find in a textbook. The resulting key ideas were discussed within our team. This was especially helpful as many of our colleagues are experienced physics teachers, and the involvement of teachers in the design process is crucial in order to create a teaching-learning sequence that can be successfully implemented into the “real classroom” [13].

We base the learning goals for our TLS on the work of Plotz. He proposed concepts, which students should comprehend after mandatory education: the propagation of radiation, the order in the spectrum, its omnipresence, the transportation of energy and the interaction with matter [6].

During our development process, a question arose very quickly: Is it better to introduce electromagnetic radiation in the wave or in the particle model? The problem is that neither model is part of the middle school education in Austria, meaning one would have to invest time into explaining one of those models before moving on to electromagnetic radiation. We realised that there was a third option, which we call “the geometrical optics approach”: light, a small but vital part of the electromagnetic radiation, is a well-researched topic in physics education. The Austrian curriculum manages to cover geometrical optics without introducing the wave nor the particle model. So why should this not also apply for the rest of the electromagnetic spectrum? It became clear to us that many features of Haagen-Schützenhöfers curriculum on geometrical optics (as mentioned in 2.2) might be transferable to the whole spectrum. The learning path that resulted from our decision to build on the geometrical optics curriculum is described in the following.
3.2. The learning path
The prototype of our TLS is divided into three segments. First, the students learn the key characteristics of electromagnetic radiation. We followed the suggestion made by Plotz to include the speed of radiation and also drew on the finding of Haagen-Schützenhöfer which states that distinguishing between matter and light is indispensable.

Next, the students learn about the interaction of radiation with matter. This is done by focussing on reflection, absorption and transmission. We decided not to introduce too many new technical terms for the students to learn in our TLS. Therefore, we did not include the concept of radiation flux in our TLS. Instead, we talk about the “amount of radiation” and that “a part of the radiation is absorbed”, drawing on words that are already familiar to students. In the corresponding part of the instruction, we implement a graphical representation where the propagation of radiation is depicted as arrows (see figure 1). Explanations and experiments that involve the interaction of electromagnetic radiation with matter are always depicted through such illustrations. This graphical representation was adapted from Haagen-Schützenhöfer’s work.

In the third segment, the link between energy and electromagnetic radiation is established. The phrase “radiation carries energy” is based on the work from Quinn [14], where she elaborates on the relation between those entities and settles on this formulation.

We decided not to discuss the interaction with matter on the atomic level, as we found this rather difficult for students at this age. Our hypothesis was that students would find it plausible that the transfer of energy to matter leads to various effects, thus helping to explain the impact of radiation on matter later in the teaching and learning sequence. Furthermore, the difference between ionizing and nonionizing could be explained with energy, as we estimate that students might find it quite plausible that radiation carrying more energy is more dangerous than radiation carrying less energy.

We find it important to show that they key ideas apply to every type of radiation. For the investigations presented in this paper, we decided to illustrate every key idea with visible light, as students are familiar with it. Then, every key idea is applied to infrared radiation, as this allows the students to experience a type of radiation that is nonvisible, but still easy to experiment with, as it is can sensed as heat. Next, every idea is applied to radio waves, a type of radiation that cannot be sensed in any way. It should be pointed out that we used the term “radio radiation” in our investigations in order to avoid the term “waves”.

Figure 1. Graphical representation of the propagation of electromagnetic radiation

4. Research questions
It is important to know how students react to the elements of the instruction: Do students find the explanations given in the instruction intelligible and plausible [15]? In the conceptual change framework, those are the necessary requirements for students to accept an explanation [16]. We wanted to evaluate if the three presented key ideas fulfil those requirements. Therefore, we aim to answer the following research questions:

- Do students find the key ideas intelligible and plausible?
- Are students able to apply the key ideas to new problems?
- Which learning obstacles and which helpful elements can be identified for the specific learning content?
5. Methods
In order to answer the research questions stated above, the method of probing acceptance [15] was applied. First, we will describe this method. Then we will outline the setting of our study and give an insight into the analysis of the data.

5.1. The method of probing acceptance
The method of probing acceptance is a form of teaching experiments first proposed by Jung [15]. The inquiry is conducted with single students, which allows to closely follow their learning processes. This method has proven useful in recent research on teaching materials [11,17]. The underlying idea of this method is to present an explanation to a student and to evaluate whether the explanation is plausible and intelligible for the student and if they can apply it to a new task. Jung calls this “to accept the explanation”, hence the name of the method. This description of “acceptance” is very similar to the necessary properties for a conceptual change [16].

In our study, the prototype of the TLS was segmented in different key ideas (see table 1).

Overall, this approach gives researchers the opportunity to see how students react to the instruction and to detect learning difficulties as well as misconceptions.

5.2. Study design
For the data presented in this paper we conducted one-on-one teaching experiments using the method of probing acceptance. The teaching experiments lasted around 50 minutes and were conducted with six students individually. The students were in grade eight in a middle school in Vienna. Each student was given a code name that they are referred to in the depiction of the results.

The teaching experiments consisted of the steps that are shown in table 1: The key idea was presented to the student and illustrated with an example. The student was asked to assess and rephrase the key idea. Next, the student had to solve two tasks (see table 1). The tasks were designed to create opportunities to see if the student applies the presented explanation to electromagnetic radiation other than visible light (namely infrared and radio radiation) and to evaluate if he or she is able to use the explanation correctly. This procedure was conducted for every key idea.

Table 1. The explanations, examples and tasks used in the teaching experiments and the intended solutions of the tasks.

| Key idea (“explanation”) | Illustrating examples | Task 1 |
|--------------------------|-----------------------|--------|
| Electromagnetic radiation is different than matter! It cannot be touched, it has no mass, it propagates really fast – nothing is faster than radiation! | It is shown that light cannot be touched, and that light reaches the other end of the room without a noticeable delay, demonstrating that light propagates really fast. | The student is presented with a ceramic heater that emits infrared radiation. He/she has to give reasons that the source emits electromagnetic radiation. |
| Electromagnetic radiation propagates until it encounters matter. A part of the radiation is transmitted, a part is reflected, a part absorbed. The amount of electromagnetic radiation that is transmitted, reflected and absorbed depends on the type of radiation and matter. | Demonstration of absorption, reflection and transmission of light and IR radiation on semi-transparent paper and on water. | The student has to conduct an experiment to figure out what happens when infrared radiation encounters a piece of tinfoil. |
| Sources of electromagnetic radiation emit energy – the energy is carried by the radiation. When radiation is absorbed by matter, energy is transferred to matter. | IR radiation heats the skin and water as a result of energy transfer. | An excerpt from a school book stating that the sun is an important source of energy is presented to the student. The student has to explain how the energy from the sun gets to earth. |
Intended solution

Infrared radiation cannot be touched. It travels really fast. Infrared is electromagnetic radiation. The tinfoil is placed in front of the lamp. Behind the tinfoil you cannot feel any heat, therefore nothing is transmitted. When you hold the hand in front of the tinfoil, you can feel some heat, therefore a part of the radiation is reflected. As nothing is transmitted and only a part of the radiation is reflected, the tinfoil must also absorb some of the infrared radiation.

The sun emits radiation that carries energy.

Task 2

The student is told that radio programs are broadcasted using radio radiation. He/she has to explain that radio radiation has the properties described in the key idea.

The student has to explain whether the radio reception is better in the house or in the garden.

After discussing that the exposure to the sun has different effects on the human body, the student is asked why this happens.

Intended solution

Radio radiation cannot be touched. It travels really fast, as the program broadcasted can be received almost instantly over long distances. Radio radiation is electromagnetic radiation. If the radio is placed in the house, less radiation gets to the radio compared to a radio placed outside, as parts of the radiation might be absorbed and reflected by the walls of the house.

When we are exposed to the sun, we absorb some of the radiation the sun emits. That way, energy is transferred to our body, which leads to various effects.

5.3. Analysis of the data

The interviews were recorded and transcribed. The transcripts were analysed with the method of evaluative qualitative text analysis [18], using a deductive coding manual. For every part of the teaching experiment, it is coded if the student’s performance was good, satisfactory or insufficient. The results are depicted in a profile matrix to enable to look at the data in a case-oriented as well as a topic-oriented perspective [11,18]. The categories for the paraphrases and the task solving were specific for each step of the investigation, but a general overview can be found in table 2. One of the interviews was also analysed by a colleague, resulting in a Cohen’s kappa coefficient of 0.76, which means a good interrater reliability [19].

Table 2. Overview of the categories for the evaluative content analysis

| Category       | Good ✔ | Satisfactory ~ | Insufficient × |
|----------------|--------|----------------|----------------|
| Assessment     | The student finds the key idea plausible and intelligible. | The student finds the key idea overall plausible but expresses some doubts. | The student does not find the key idea intelligible. |
| Rephrasing     | The student includes all the important aspects in their paraphrasing. | The student leaves a part of the key idea out OR makes a minor mistake. | The student is not able to rephrase it or makes more than one mistake. |
| Task solving   | The student applies the presented key idea to the problem and can solve it. Only one small assistance is needed from the teacher. | The student can solve the task with some assistance from the teacher. | The student is not able to solve it or makes mistakes while doing so. |
6. Findings
In the following, the results of the content analysis for each key idea are presented and the problems that arose are explained briefly. In some cases, an answer could not be coded due to missing data.

6.1. Introduction of the term of electromagnetic radiation
As it can be seen in table 3, the students rate this key idea as plausible. The problem that occurred in the paraphrasing was that Emma argued that radiation is visible. Most students faced difficulties in one of the tasks. In all cases that were marked as “satisfactory” or “insufficient”, the students struggled to decide if the properties stated in the key idea apply for infrared radiation or radio waves. Emma states that the warmth of the infrared radiation is a property that all types of radiation possess. Amina and Denise argue that radio radiation can be heard by humans.

Table 3. Results for “Introduction of the term ’electromagnetic radiation’”

|                     | Amina | Beyza | Christopher | Denise | Emma | Fatima |
|---------------------|-------|-------|-------------|--------|------|--------|
| Assessment of the key idea | ✔     | ✔     | ✔           | ✔      | ✔    | ✔      |
| Rephrasing the key idea | ✔     | ✔     | ✔           | ✔      | ✔    | ✔      |
| Solving a talk involving infrared radiation | ✔   | ✔     | ✔           | ✔      | ✖    | ✔      |
| Solving a task involving radio radiation | ✔   | ✔     | ✔           | ✔      | ✔    | ✔      |

6.2. Interaction of electromagnetic radiation with matter
The results depicted in table 4 show that the students assessed this key idea well. The students also emphasized that they find the graphical representation very helpful to understand the propagation of electromagnetic radiation. The participants were able to rephrase the key idea. There were only minor difficulties in solving the task in the context of infrared radiation. Similar to 6.1, some students struggled with the radio radiation task. When asked if a radio has better reception in the house or outside, Denise and Emma did not look at the task in terms of absorption, reflection and transmission. Instead, they argued that they experienced having better radio reception indoors. To give an example: Emma: “I think you have a better reception at home”. Interviewer: “Okay, and why?” Emma: “I have no idea. I think at home you have a better reception than outside in general, as far as I know.”

Table 4. Results for “Interaction of electromagnetic radiation with matter”

|                     | Amina | Beyza | Christopher | Denise | Emma | Fatima |
|---------------------|-------|-------|-------------|--------|------|--------|
| Assessment of the key idea | ✔     | ✔     | ✔           | ✔      | ✔    | ✔      |
| Assessment of the graphical representation | ✔     | ✔     | ✔           | ✔      | ✔    | ✔      |
| Rephrasing the key idea | ✔     | ✔     | ✔           | ✔      | ✔    | ✔      |
| Solving a task about the interaction between IR and tinfoil | ✔   | ✔     | ✔           | ✔      | ✔    | ✔      |
| Solving a task about radio reception | ✔   | ✔     | ✔           | ✔      | ✔    | ✔      |
6.3. Relation between electromagnetic radiation and energy

The results in table 5 show that the key idea that radiation carries energy was evaluated positively and the students were able to rephrase this key idea adequately. However, some of the students struggled to apply the key idea to the tasks. At the task about energy transfer from the sun to the earth students did not draw a connection between the energy transfer and the radiation, focusing instead on radiation absorption in the atmosphere. Christopher and Denise also struggled to draw a connection between the absorption of energy and the impact of radiation on the human body. While Christopher was able to link the heating effect of radiation to energy, Denise was not able to see a connection at all.

|                      | Amina | Beyza | Christopher | Denise | Emma | Fatima |
|----------------------|-------|-------|-------------|--------|------|--------|
| Assessment of the key idea | ✔     | ✔     | ✔           | ~      | ✔    | ~      |
| Rephrasing the key idea        | ✔     | ✔     | ~           | ✔      | ✔    | ✔      |
| Solving a task about the transfer of Energy from the sun to our planet | ~     | ✔     | ✗           | ~      | ✔    | ✔      |
| Connecting the impact of electromagnetic radiation on the human body with the absorption of energy | ✔     | ✔     | ~           | ✗      | ✔    | ✔      |

7. Discussion

The results show that all three Key Ideas were assessed positively and the students were able to rephrase them. Some difficulties and learning obstacles surfaced when the students had to solve tasks involving radio radiation as well as the relation between electromagnetic radiation and energy. Those are interesting findings that can help to refine the prototypical TLS and help us to enhance our knowledge on misconceptions. For example, the statement from Emma, that radiation is always warm, is something that fits our experiences with teaching electromagnetic radiation. This could be a result from students’ experiences with the sun and lamps. That the radiation of the sun is connected with warmth is a student conception that was also noted by Neumann and Hopf [7].

It seems that radio radiation represents a context where students may hold conceptions that are obstacles for the intended learning outcomes, for example that radio radiation can be heard, or that you do not have a good reception outdoors. The later misconception might derive from experiences with reception when the transmitter is situated in the house, as it is the case for Wi-Fi-connections. Additionally, it seems that radio reception is not an everyday issue anymore, as many students told us during the investigation that they only listen to the radio in the car. Therefore, we recommend using other contexts, for example mobile phone radiation, Wi-Fi or Bluetooth as examples for radiation of that part of the spectrum.

Another context that lead to learning obstacles was the transfer of energy from the sun to the earth, as some students focussed on the atmosphere and the absorption of radiation. This could be a result of students trying to apply the second key idea (interaction with matter) to the task, or they might have learned about the climate and the atmosphere before. Therefore, we changed this task in subsequent investigations, looking at the energy transfer from a lamp to a solar powered calculator.

We hoped that by introducing the concept of energy, one could make the variety of impacts that electromagnetic radiation can have on the human body plausible. This worked well for four of the students, although most of them focussed on the heating effect, whereas one student could not make the connection at all.
It must be stressed that, due to the sample size, we cannot generalize our findings. This is not the aim of our study. In this phase of our project it is more valuable to look at only a few students, but follow their learning processes very closely, getting insight into students’ perspectives and possible learning obstacles. To sum it up – the results are promising, showing that this approach can work, and give insight into problems that might arise while teaching it.

8. Conclusion & Outlook
In this paper we outlined our approach to implement the topic of electromagnetic radiation at the middle school level. We presented our results from a first investigation, evaluating the key ideas we formulated to introduce electromagnetic radiation, its interaction with matter and the transportation of energy. We found that those key ideas worked quite well for our sample of students. We were able to pinpoint learning obstacles and got a better grasp of the perspectives that students might bring to the classroom. The results help us to adapt the key ideas as well as the illustrating examples and tasks, leading to a refined draft of the TLS. Probably the most important outcome is that it is possible to explain electromagnetic radiation without waves or particles, and that the instructional designs we derived from geometrical optics are well received by students. The adaption of the key ideas and the results of the following investigation are presented in [20].

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