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Experiments in Physics Education: Designing Activities & Research

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Introduction

This habilitation thesis is a compilation of selected publications resulting from my involvement in the community of active physics performers and educators as well as my participation in physics education research. This divergence of my professional orientation leads to the fact that this habilitation thesis is also composed of two logical parts that share a common introductory theory (Chapter 1) and the common denominator of which is the issue of using experiments and practical work in physics teaching and learning.

Chapter 2, describing the first logical part of my work, is based on my many years of experience as a designer of experimental activities and materials related to both lecture demonstrations and students' hands-on experiments. Following my dissertation thesis, in which I had been designing experimental activities for physics lessons, I published four original papers in The Physics Teacher and Physics Education journals with readership consisting mainly of practising teachers. These papers introduce newly designed experiments concerning thermal phenomena and they are intended to serve as a source of inspiration for upper secondary school teachers, providing them with annotated methodological notes. In three of the four articles, the dominant experimental technique used is infrared thermal imaging, which is rapidly gaining ground in physics education and allows previously unfeasible experiments to be carried out.

Chapter 3 addresses my current research focus. After completing my PhD, I started looking at physics experiments more generally and not only in the field of thermodynamics or even just thermal imaging. Gradually, my main research interest became students' intrinsic motivation towards experimental activities, the studies of which create the second logical part of this habilitation. Together with my colleague Marie Snětinová, we gradually formed a research team working on this issue involving colleagues from the Faculty of Mathematics and Physics, Charles University and the Faculty of Education, Charles University. The current results are presented in three already published studies; the fourth most complex one is being prepared.

Notes on terminology:

- In this work, the terms *student* and *pupil* are used for learners. Where it is possible to distinguish (for example, in research studies) which level of education is involved, the term *pupil* is used for the lower secondary level and the term *student* for the upper secondary or undergraduate levels. If the age of the learner is not specified or if general statements are made, the term *student* is used.
- In this work, the terms *thermal imaging camera*, *thermal camera,* and *infrared camera* are used interchangeably.

1. Experiments in physics education

"The test of all knowledge is experiment. Experiment is the sole judge of scientific truth."
R. P. Feynman

Nowadays, almost no one doubts that experiment has an important role not only in scientific research as such but also in science teaching and learning. However, for several decades, scholars and instructors involved in educational research have had an extensive debate about what this role actually is. And along with this question, other, closely related ones may come to one's mind: What are the functions of a science experiment when it is conducted by the lecturer and when by the students themselves? Which of these two options is more effective and under what conditions? Which methods and forms of instruction promote the benefits of experimentation and which limit it? Are there students who benefit from experiments more than others – and why? When does a classroom experiment still provide a sufficiently real image of the world and when is it only a poor, artificial imitation of it?

These and many other issues are filling the pages of field-relevant journals, and the answers we get are inevitably only temporary – the fundamental "research material" we work with, i.e., pupils and students, changes under our hands as today's society evolves. Therefore, many of the fundamental questions of science education remain permanently relevant, and both current and future researchers and practitioners will have to answer them again and again, in the context of their era, country, or culture.

Nevertheless, in this chapter, I attempt to summarize the current view and related research on the different roles and functions of experiments in science education.

1.1. The relation of scientific theory and experiment

Although the quote that introduces this chapter refers to science in general, it is not surprising that its author is one of the most famous physicists of the 20th century. Among all sciences, it is physics and its historical development from Galileo to the present that provides perhaps the clearest example of experiment as a key criterion of truth. However, historically, this criterion was applied at different stages of the scientific process, depending on the currently prevailing scientific paradigm or the importance attributed to empirical evidence in each era (Novotný & Svobodová, 2014).

During the 19th century, *empiricism* was the defining philosophy in science, putting emphasis on inductive inquiry methods (Duit & Tesch, 2010). The typical inductive sequence of instructional phases can be simplified as *problem* → *observation, experimentation, measurement* → *analysis of results* → *conclusion and generalization*; and it plays a significant role in science instruction to this day. In this approach, experiment serves as a tool for building new knowledge (theory) itself.

The 20th century brought a critique of empiricism and uncovered its weak points (Popper, 1945). *Rationalism* became the new leading paradigm of science, characterized by theory-driven deductive reasoning the results of which are confronted with empirical data. In other words, hypotheses are formulated based on a known or assumed theory, and experiments (coming at the end of the cognitive process) are designed to confirm or, more likely, to refute these hypotheses.

Based on the above, we feel that pure empiricism and pure rationalism represent two extreme, opposite ideological positions, neither of which corresponds to the actual relationship between theory and experiment. During scientific work, theory and experiment are not bound by a relationship of subordination/superiority or by a relationship of unilateral succession (Maršák & Janoušková, 2008a, 2008b), but they represent two equal, inseparable components whose interaction is a cyclical process (Duit & Tesch, 2010).

In the field of science education, the relationship between theory and experiment is currently viewed in a similar way – both traditional science content (concepts, laws, and principles) and methods of inquiry (observation, experiment) are considered equally important issues of instruction (Duit & Tesch, 2010). Experiments can naturally serve both as a tool for constructing new knowledge – Koponen and Mäntylä (2006) refer to this role of experiments as *generative* – and as a verifying tool, depending on the learning situation. However, researchers attribute many other roles and functions to science experiments; to understand them deeper, let me now divide experiments into lecture demonstrations and students' practical work, according to who their key protagonist is.[1]

Although there will be more emphasis on physics education in the following text, many of the experience and research findings were obtained in the broader context of science education.

[1] From now on, I will no longer deal with thought experiments.

1.2. Lecture demonstrations

Lecture demonstrations (from Latin: *dēmōnstrāre* = to show) have long been an inherent part of physics instruction. In a traditional sense, lecture demonstrations are teacher-centred, while the role of students is passive and mainly consists of observation. Although the term "lecture" refers to undergraduate lectures taking place in large university auditoriums, demonstrations are also deeply rooted as a part of secondary education and will be seen as such in the following text.

Lecture demonstrations and conceptual understanding

In the last decade of the 20th century and the first decade of the 21st century, traditional lecture demonstrations and their benefits became the subject of extensive debate. Following the constructivist approach, many researchers focused on the issue of conceptual understanding at that time. Using conceptual tests (e.g., Hestenes et al., 1992; Maloney et al., 2001; Yeo & Zadnik, 2001; Tongchai et al., 2009), large-scaled studies across all physics domains identified serious students' conceptual difficulties and revealed dozens of *misconceptions* (also *alternative conceptions* or *naive beliefs*). The turn of the millennium was marked by looking for ways and strategies of facing these misconceptions and stimulating conceptual change. In many studies, traditionally led lecture demonstrations proved to be rather ineffective in promoting students' conceptual understanding (Roth et al., 1997; Crouch et al., 2004; Milner-Bolotin et al., 2007). The research also showed that to obtain better learning gains, it is essential to design demonstrations as a more student-centred activity.

This idea was already applied by White and Gunstone (1992) who proposed an approach called *predict – observe – explain* (POE). In the spirit of constructivism, this strategy builds on initial students' predictions that are usually based on their personal everyday experience and that precede the actual execution of the demonstration. Today, POE is a label for a whole family of strategies, the most prominent representative of which in physics being the Interactive Lecture Demonstrations (ILDs) introduced by Sokoloff and Thornton who had described the progress of the instruction step by step (Sokoloff & Thornton, 1997). These demonstrations are often deliberately designed to foster conceptual change by using cognitive conflict as a key instructional strategy (Zimrot & Ashkenazi, 2007). Ideally, the discrepancy between students' expectations and the actual outcome of the demonstration should arouse a feeling of dissatisfaction with their own understanding and promote the desire to understand the correct scientific explanation. In fact, intentionally induced cognitive conflict is regarded as somewhat controversial and its benefits and risks are widely discussed by Limón (2001) or Heywood and Parker (2010).

The studies addressing ILDs have shown that the crucial element of the POE chain for the effectiveness of conceptual understanding is the first part of the chain, i.e., the prediction (Milner-Bolotin et al., 2007; Zimrot & Ashkenazi, 2007; Miller et al., 2013). The fact that students are encouraged to make a prediction of the experimental outcome before actually observing it positively affects the learning gain; some authors even state that this is true regardless of whether the prediction was scientifically correct or not (Miller et al., 2013). What was identified as another predictor of more effective conceptual learning from demonstrations was the opportunity to discuss one's personal prediction with peers before observing the experiment (Milner-Bolotin et al., 2007). On the other hand, successful implementation of ILDs requires technical support staff and additional time, especially when starting with this approach (Sharma et al., 2010).

Together with the covid-19 pandemic, the rapid development of technology worldwide is likely to lead to more intensive research comparing effectivity of live versus online lecture demonstrations. Such studies are already emerging – on an example of two demonstrations in mechanics, Kestin et al. (2020) show that students can learn more from online experiments than from live ones, while enjoying both forms comparably. However, much follow-up research will be needed to draw more general conclusions from a long-term perspective. After all, as Austin and Sullivan (2019) state, there is generally a lack of longitudinal studies examining the long-term effects of science performances.

Affective and motivational aspects of lecture demonstrations

So far, I have looked at lecture demonstrations only through the prism of scientific knowledge transfer and concluded that their effectiveness in developing conceptual understanding is questionable and depends on their interactivity. However, the criticism associated with this weakness of lecture demonstrations has mobilized their proponents who point out that even teacher-centred performances have their specific functions in the classroom (McCrory, 2013). Thus, more research attention has been paid to the motivational potential of lecture demonstrations – after all, the constructivist paradigm assumes a motivated learner to be a prerequisite for meaningful learning.

Lecture demonstrations are primarily related to (triggered) situational interest, which is a short-term form of motivation driven by a specific situation that captures students' attention and curiosity. In the study presented by Walton (2002), the overwhelming majority of students declared that demonstrations helped them to keep interest during the lecture. Palmer (2009) proved that students' situational interest is stimulated during the observation and explanation of demonstrations; according to his work, only conducting experiments by students themselves has a stronger motivational impact. Similarly, Lin et al. (2013) found situational interest to be well maintained by two activities: lecture demonstrations and hands-on experiments with elements of novelty and aesthetics. Kácovský and Snětinová (2021) confirmed the important role of physics demonstrations in interest development and concluded that interest in demonstrations increases with students' self-reported giftedness and diligence in physics.

Given the current trend of declining interest in science education, the studies of situational interest and its stimulation can be expected to increase in importance, as situational interest is an important starting point for the development of individual interest, a more advanced stage of interest (Hidi & Renninger, 2006) that is directly related to career choice.

Leaving motivational aspects aside, lecture demonstrations are also believed to illustrate abstract situations and to interlink classroom content with real life (Di Stefano, 1996).

1.3. Practical work

Among science educators, the term practical work is often interpreted intuitively. In this thesis, I follow the definition given by Millar (2010) who refers to practical work as *"any science teaching and learning activity in which the students, working individually or in small groups, observe and/or manipulate the objects or materials they are studying"* (p. 109). This definition does not include work with data like some previous definitions do (Lunetta et al., 2007); nor does it consider lecture demonstrations as a type of practical work.

The most common form of practical work is obviously laboratory work, but practical work also covers other classroom activities that do not have the nature of laboratory work – e.g., short practical episodes incorporated into regular classes.

Practical work is an inherent part of science education and provides a link between two domains of knowledge – the domain of observables and the abstract domain of ideas (Millar et al., 1999; see Figure 1.1). Traditionally, practical work has been attributed and expected to have many functions and roles. Different authors presented various frameworks which, however, overlap significantly: usually, they describe practical work as a means of enhancing conceptual learning, stimulating interest, gaining insight into scientific methods and approaches, or understanding the nature of science (e.g., Kerr, 1963; Hodson 1990; Hofstein & Lunetta, 2004). Among the recently published books, let us mention the work of Wellington and Ireson (2017) who define four roles that practical work should play, namely developing skills, illuminating/illustrating (concepts, laws…), motivating/stimulating (curiosity, interest…) and challenging/confronting (what if…?).

In the following subsections, I will try to address the aspects above in more detail.

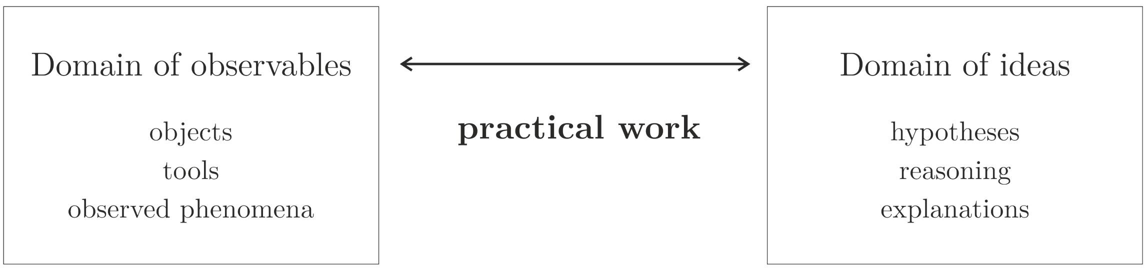

Figure 1.1: Practical work as perceived by Millar et al. (1999).

Practical work and conceptual understanding

Among science educators, it is widely believed that practical work is essential in improving conceptual understanding, as expressed by the popular slogan *learning by doing*, which gained wider awareness thanks to the American philosopher and psychologist John Dewey. However, reliable evidence that practical work really leads to better understanding – compared to e.g., lecture demonstrations or instruction with only minimal involvement of experimental activities – is still missing.

The intensive research of the previous decades was accompanied by a plethora of studies in this field, which often produced contradictory results. However, the conclusions of large meta-analyses do not provide general grounds for declaring practical work a more effective teaching method than other methods. For example, Hewson and Hewson (1983) reported a significant contribution of practical-based instruction to conceptual understanding; yet in the same year, Bredderman (1983) only found a modest positive effect of activity-based lessons on knowledge development in his large-scale study. A decade later, Hodson (1993) or Lazarowitz and Tamir (1994) concluded that practical work does not outperform other methods in gaining knowledge of scientific facts; Bennett (2003) made similar conclusions. Hodson (1991) even says that, given its time-consuming nature, practical work is often unproductive and lacks real educational value. Millar (2010) pointed out that students often remember episodes related to the experimental process rather than explanations and explanatory ideas. Compiling results from six extensive research reviews (Bates, 1978; Hofstein & Lunetta, 1982, 2004; Lunetta et al, 2007; Garrett & Roberts, 1982; Hodson, 1993), van den Berg (2009) stated that laboratory work – as implemented in school practice – is not better than other methods in teaching science concepts and content.

What explains the unconvincing effect of practical work on conceptual understanding is the fact that it is the quality of practical work that matters rather than only its presence in the instruction. Therefore, researchers focused more deeply on what features make practical work effective and, on the contrary, what should be avoided.

The first observation is that practical work is sometimes simply conceived as too demanding, especially if students are new to it. Bennett (2003) states that practical work often requires students to do many sub-activities simultaneously (working with instructions, using instruments, taking measurements, creating records, etc.) that end up completely overshadowing the domain of ideas. Abrahams (2007) calls this *cognitive overload*, which occurs when students have to use both intellectual and practical skills simultaneously as well as their prior knowledge; cognitive overload results in ineffective – if any – learning.

Abrahams and Millar (2008) suggest that the effectiveness of practical work actually involves two components, one associated with the domain of observables and the other with the domain of ideas; the latter also covers conceptual understanding. However, the same authors state that only *"few practical lessons are designed to stimulate an interplay between observations and ideas"* (p. 1965) during the practical activity itself.

As to the probably most reported significant barrier to effective development of conceptual understanding, various studies repeatedly refer to the popularity of recipe-following laboratory instructions addressed to students when performing practical activities. Why do teachers use this approach so often, although it sometimes leads students to follow purely mechanical instructions without any cognitive effort of their own? There are pragmatic reasons here – cookbooks either help teachers to cope with the limited time they can devote to practical work, or they can also lead students with minimal laboratory skills to the "right" answers more straightforwardly than a more open level of inquiry (Trumper, 2003). However, recipes have obvious downsides. Reputable studies point out that – in Millar's terminology – the cookbook-like design focuses students' attention on the domain of observables rather than the domain of ideas. For instance, Tiberghien et al. (2001) inspected 165 laboratory instruction sheets from biology, chemistry, and physics (75 at the upper secondary level and 90 at the university level) and concluded that they put more emphasis on observables than explanatory ideas. Millar (2010) explicitly states that cookbooks *"result in activities which may be hands-on but are rarely minds-on"* (p. 116). In agreement, Abrahams and Reiss (2012) point out that teachers, when preparing hands-on activities, often think in detail about what they want students to do, but rarely plan what scientific ideas they want their students to learn and how. Sharpe and Abrahams (2020) describe possible consequences of such an approach, concluding that *"when they [students] were asked to explain what they learnt from practical work they were only able to describe what they did and what they saw"* (p. 101).

Research showed that an overemphasis on observables leads teachers to rely on the assumption that if students accurately follow the instructions given, explanatory ideas will somehow implicitly arise from data or student experience during the course of the practical activity (Millar, 2010). However, explanations and generalizations trivial for teachers are simply not obvious to learners and typically do not spontaneously "emerge" in their minds (Abrahams & Millar, 2008). Abrahams and Reiss (2012) state that pure observation and manipulation with equipment and phenomena are unlikely to make students understand scientific ideas and concepts without appropriate scaffolding provided by a teacher. These authors also paraphrased the conclusions of Gunstone (1991) that *"students must be helped not only to do and see what the teacher wants but, equally importantly, to think about their observations in a particular way"* (p. 1051).

So, what recommendations can be derived from research? First, authors (e.g., Abrahams & Reiss, 2012) advise teachers who prepare practical tasks to plan purposefully and explicitly the way they will connect scientific ideas to the phenomena observed, with an emphasis on ideas. Like lecture demonstrations, the POE approach (White & Gunstone, 1992) and its derivatives appear to be a suitable way to activate students' thinking and reasoning in the domain of ideas. Further, before starting a laboratory task, students should have a basic understanding of the fundamental concepts they will be addressing, because relying on a sudden conceptual "awakening" during practical work is too optimistic.

Affective and motivational aspects of practical work

As in the case of lecture demonstrations, teachers sometimes tend to use practical work to present science (which is usually perceived by students as boring and difficult) "in a better light", i.e., as an engaging and enjoyable subject. Let us now leave aside the fact that this approach gives a distorted image of science and rarely leads to effective learning of ideas (Abrahams, 2007) – the truth is that research provides reliable evidence that students actually prefer practical work to other forms of instruction (Bennett, 2003; Cerini et al., 2003; Owen et al., 2008; Sharpe & Abrahams, 2020).

The reasons why practical work is mostly liked by students are certainly worth considering – although e.g., Bennett (2003) admits that these reasons are not always obvious. Referring to other research, e.g., Gardner and Gauld (1990) note that what students value in practical work is typically not what they actually learn. Hodson (1993) even adds that for many students, the lab environment may have *"little relevance to everyday life"* (p. 92).

The research, therefore, suggests that the reasons for the popularity of practical work are often independent of its science content. According to Gardner and Gauld (1990), practical work allows students to interact with their teacher and classmates in a less serious atmosphere and to manage their work at their own pace. Bennett (2003) adds that practical work serves students as an escape from the boring routine of writing, reading, or listening to the teacher. Students value that they can "legally" talk to their mates (Sharpe & Abrahams, 2020), which, of course, allows them to pursue topics unrelated to the science investigation itself. In conclusions to his research, Abrahams (2009) suggests that when students say they "like practical work", they are more likely to say they prefer it to non-practical teaching episodes; additionally, in the upper grades, the group of such minded students grows larger (Abrahams, 2009; Sharpe & Abrahams, 2020) and the "true fans" of practical work dwindle. Generally, as students move through secondary education, the emphasis that teachers place on interest development through practical work gradually fades (Kerr, 1963; Wellington & Ireson, 2017).

The above perspectives lead us to the conclusion that the aforementioned popularity of practical work is not popularity in the sense of long-term motivation to do practical work, but an expression of situational interest in a particular activity; this situational interest, moreover, is often not saturated with the scientific content of the activity. Research papers more or less confirm the role of practical work as a means of triggering situational interest. For instance, Abrahams (2009) in his study proves that practical work, especially when repeatedly involved in science lessons, generates non-enduring, short-term engagement in learners aged 11–16. However, at the same time he concludes that for developing long-term individual interest, practical work is quite ineffective. Similarly, practical work has probably only limited power to motivate students to choose science as their future study (Bennett, 2003; Abrahams, 2009).

Although I have stated that positive perceptions of practical work are often not based on what students actually do, it is not the case of negative perceptions – they may arise as a consequence of an inappropriate assignment or realization of practical work. Research studies provide recommendations on how to avoid discouraging students. Referring to both his own and previous research, Hodson (1990) states that for students, practical work is generally more motivating if the assignment provides an appropriate challenge and students have some control over and some independence in what they have to do. Especially the optimal level of students' independence seems to be crucial for their positive attitude towards practical work – on the one hand, Kempa and Diaz (1990) showed that students do not like practical work with over-precise instructions, on the other hand, Hodson (1990) emphasizes that the purpose of practical work should be clear. Harlen (1999) adds that lab work should give students a sense of achievement and relevance to everyday life. Finally, an expected but difficult-to-achieve criterion of students' "satisfaction with practical work" is the requirement that it works "properly", i.e., it provides results consistent with the assumptions or theory (Hodson, 1990; Sharpe & Abrahams, 2020).

Finally, let us mention one remarkable observation: While recipe-like labs are accused of low gain in conceptual understanding, they do not seem to be less valuable than more open inquiry in terms of students' motivation and interest.

Scientific skills

Practical work is often associated with skills development. Hodson (1990) distinguishes between science-specific skills intended to serve future scientists or researchers (e.g., operating a microscope, manipulating a particular apparatus, etc.) and generalizable skills applicable outside the laboratory and possibly useful also for non-scientists. Hodson (unlike e.g., Bennet, 2003) doubts that students who are not planning a scientific career should be taught science-specific skills and recommends teaching only those skills that are relevant to further education.

On the other hand, the importance of generalizable skills is crucial for some educators. Practical work is the mantra of those who consider the development of content-independent skills transferable beyond the school setting to be the primary mission of science education. These so-called *science process skills* include observing, classifying, formulating questions, making and testing predictions and hypotheses, designing experiments, collecting evidence and interpreting them, etc. Due to the possibility to use them in the out-of-school context, these skills should be more enduring than content-oriented knowledge (Millar, 2010). However, the transferability of scientific process skills to other, new contexts has been repeatedly questioned. Bennet (2003) denotes this as an open question and adds that psychologists consider such transferability to be problematic. Millar (2010) refers to extensive APU research that has shown that students' performance on tasks involving science process skills is strongly dependent on content. In other words, the inter-situational transfer is probably very limited, and students' performance is rather influenced by what knowledge they have in the field of investigation than by their science process skills. Another conclusion of the APU study (later confirmed by more recent research) may even sound paradoxically: students perform better investigations in scientific contexts than those inspired by phenomena from everyday life where they do not feel the need to use scientific habits (Millar, 2010).

Finally, if there are some conflicting results of research on skills discussed in this section, there is one area of apparent agreement across studies. Researchers consistently show that students who have had the opportunity to do hands-on practical work are – unsurprisingly – more skilled at manipulating lab equipment and performing common laboratory procedures (supportive studies are summarized in Millar, 2010).

The scientific method, scientific reasoning

Before we ask the question of whether and – if so – how practical work contributes to mastering the scientific method of investigation, let me pause on what the scientific method actually is. Among researchers, there is no consensus on its definition (Bennett, 2003), and some question the very existence of the scientific method (Dillon & Osborne, 2010), pointing out that there is no general method, no universal set of steps and rules that would lead to the development of scientific knowledge. Bennett proposes to understand the scientific method in a broader sense as *"the way in which scientific knowledge progresses"* (p. 84); however, she admits that even such a definition is non-specific. This is because the very construction of scientific knowledge has been perceived differently over time. In the first half of the 20th century, an inductive approach to science prevailed, assuming that all knowledge is constructed by putting into context the particulars obtained by observation and experiment. Today, however, a different, deductive approach prevails, characterised by the construction of knowledge by the formulation and testing of hypotheses, which is now strongly emphasised in investigative school practical work. According to the studies summarized by Bennett (2003), the latter approach is probably closer to students as they perceive practical work as a tool to verify what is already known (to achieve "the right results") rather than as a way to build new scientific ideas.

If we focus on the link between the acquisition of the scientific method and practical work, we do not get very convincing conclusions. Hodson (1990) talks about how practical work often provides incoherent understandings of scientific methodology. Harlen (1999) states that *"findings from research on the effect of practical work on students' understanding of the nature of scientific enquiry are as negative as those for conceptual understanding"* (p. 10). Summarizing the results of several studies a decade later, Millar (2010) reports that in relation to investigative practical work, *"general conclusions about scientific reasoning are not strongly supported"* (p. 125). Bennett (2003) points out that what is more important than learning some sequence of rules about how to proceed scientifically (which other authors argue does not even exist), in real science, is observing scientists' decisions about what to observe, how to interpret data and what conclusions to draw from them.

Nature of science

Some researchers also hope that practical work helps students learn about what is referred to as *the nature of science* (NOS). This includes, for example, the recognition that the world is principally "describable in the language of science" and the understanding of important features of scientific knowledge. As Lederman (2007) summarizes, scientific knowledge is empirically based, but built with creativity, theory-laden, but influenced by culture and the scientist's personality. What learners often neglect is the admission that scientific knowledge is not absolute and "already completed", but principally tentative and open to change. Some students also see scientific knowledge as strictly reflecting reality, thus excluding the possibility of testing the agreement between these two (Carey et al., 1989).

Researchers warn that teaching solely about the content and methods of science is not sufficient to develop an understanding of what the NOS actually is; it needs to be emphasized explicitly (Lederman & Abd-el-Khalick, 1998). Although the work of Carey et al. (1989) suggests that carefully designed practical work could show an impact on understanding the NOS, according to Millar (2010), there is *"little research evidence on the effectiveness of practical work that has been explicitly designed to develop students' understandings of the nature of science"* (p. 131). Moreover, in this decade, research in this area (i.e., the relation of the NOS and practical work) has rather died down.

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To avoid any doubt regarding the message of this entire section: Based on my own experience of teaching at high school and university, I personally consider practical/laboratory work to be an essential part of science education, and even more so of physics education. On the other hand, from the perspective of a researcher, I feel the need to point out that the expectations we (as educators) have of practical work are sometimes overly ambitious.

As I have tried to illustrate above, in many important aspects of science education (such as conceptual understanding, development of scientific methods and skills, long-term individual interest…), the results of individual studies and meta-analyses do not provide clear support for the conclusion that practical work convincingly outperforms other teaching methods. On the other hand, much of this research acknowledges that practical work is practised in different forms and in different quality, which can hardly be described and addressed in all its complexity in research papers. More than anything else, the cited research often reflects a kind of "average" level at which practical work is usually practised, so that precisely and meaningfully designed activities may perform some functions much better than the results of the studies suggest.

The more specific recommendations for practice have already been mentioned in this section, so let me now conclude with the general ones: The teacher should plan practical work with a clear aim and not just with the intuitive belief that "it is good for students to experiment on their own". It is important for the teacher to clarify in advance which of the many aspects of practical work is to be predominantly developed – whether it is primarily the acquisition of knowledge, the acquisition of laboratory skills, the understanding of the scientific method, the stimulation of interest, etc. Trying to develop "a little bit of everything" can lead to the purpose of the activity being unclear to students and its overall benefit being minimal. Therefore, it is advisable to focus on a specific goal – and make it explicit to the students. If the teacher's goal is to show that a fundamental tool of physics as a science is creating and testing hypotheses, his/her students should know this. It is not enough to rely on the students' implicit understanding of the teacher's goals, as they are more likely to focus on the physics content of the experiment itself.

It is also natural to require for the difficulty of the practical work to increase in proportion to the students' experience, both in terms of the physics content and the methods used to obtain and process the data. For instance, the widely used approach of making high school students learn how to statistically evaluate quantitative experimental data in two hours at the beginning of the school year and assuming they know how to do so for the rest of the year is far from appropriate from this perspective. Such a task is difficult for students at the beginning, so they solve it mechanically, without understanding; however, because the difficulty of the task does not increase over time, they make do with this mechanical approach for the rest of the year. Let us emphasize here that developing all the roles of practical work discussed in this section is a long run that cannot be successful, unless it is built on solid but gradually developed foundations.

2. Designing experiments in the era of technologies: The case of thermal imaging

Before turning to experiments in physics education, let me begin this chapter with a more general, personally motivated introduction. We are living in a time of unprecedented technological development that is transforming our daily functioning, and our daily lives. We have stopped sending letters, we use our phones for all sorts of things, not just for making calls, we have got rid of compact discs and gigabytes of our data are stored somewhere in the cloud. We do not need to remember phone numbers or timetables, we can get by without a paper map in a foreign city, and we are caught off guard when someone asks for cash. We work and communicate in a completely different way than we did, say, twenty years ago.

And then there's the school. Education has traditionally been perceived as a very conservative segment of society with a resistance to change and a tendency to stay in the rut – seemingly the true opposite of technological innovations. Even because of this contrast, today's critics of the current educational system (at least, but certainly not only in the Czech Republic) are so fond of blaming schools for their cumbersomeness and lack of educational content relevance for the current generation of students. This may be partly a cheap criticism, but the demand that school reality (including technological equipment) be relevant to students' everyday life is justified.

For the avoidance of doubt: In general, I personally think that a certain conservatism in education is important, as it ensures continuity and protects against short-term fashion trends in education or random interventions of political representation that occur from time to time; moreover, the availability and personal capabilities of many teachers simply do not allow them to keep up with the technological innovations of recent years. However, I find it reasonable that in schools of all types, we should try to keep track of how the world around us is technologically changing, pick out what has proven useful in real life and meaningfully incorporate it into teaching practice where relevant. The recent experience with the new coronavirus has shown us that education is capable of such a transformation. After the outbreak of covid-19, both teachers and students had to flexibly adapt to a new, unknown situation in an unprecedentedly short time. Studies describing how the pandemic has affected education are being prepared across the world these days, but one common conclusion can already be anticipated – distance education has undoubtedly improved teachers' technological pedagogical knowledge by leaps and bounds. If there has ever been a perfect time to bring contemporary technologies familiar from everyday life into the classroom, it is just now.

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Section 2.1 of this chapter focuses on introducing technologies into teaching in general, and more specifically into the innovations of physics experiments. Sections 2.2 and 2.3 aim to briefly introduce the technological area that has been my dominant focus in designing experimental activities – that is, infrared thermal imaging.

2.1. Technologies in physics experiments: Barriers and expectations

In the field of physics experiments (both lecture demonstrations and practical work), technological innovations offer huge opportunities – almost all new digital devices entering everyday life can potentially become experimental tools for physics lessons. Thus, devices used primarily in science or industry have penetrated classrooms in the last decades – sets of various sensors (platforms adapted to school environment such as Arduino, Vernier, PASCO, Lego Mindstorms, NeuLog, etc.), data loggers, digital microscopes, thermal imaging cameras, etc. Physics teachers, together with their colleagues teaching ICT, also often participate in introducing augmented/virtual reality or 3D printing into their schools. Especially 3D printing is very welcome by physics teachers since it enables them to produce simple lab aids. What is particularly important in physics education are the highly "addictive" smart devices such as smartphones, tablets, or laptops, which are routinely used by students both in and out of school. When conducting physics experiments, smart devices can serve as both data-collecting and data-processing devices; in both cases, it is a great challenge for teachers to find strategies of how to integrate them into physics lessons meaningfully.

Certainly, introducing new technologies into physics experiments has its pitfalls, which do not differ from those occurring when introducing innovative devices into education in general. The barriers that inhibit the integration of technology into teaching have been amply described in the literature over the past two decades. A notable milestone is a paper published by Ertmer (1999), proposing a division between first- and second-order barriers. First-order barriers refer to influences external to the teacher, such as demands on time, money, equipment, or training; second-order barriers are *"rooted in teachers' underlying beliefs about teaching and learning"* (Ertmer, 1999, p. 51) and involve teacher's attitudes, confidence, personality, self-efficacy, etc. Although first- and second-order barriers are linked together and influence each other (Hew & Brush, 2007), many researchers agree that as technological development continues, the importance of first-order barriers (at least in Western countries) is declining, while second-order barriers remain a significant obstacle (Durff & Carter, 2019; Ertmer, 2015; Ertmer et al., 2012). After all, already Hew and Brush (2007) in their meta-analysis identified two second-order barriers among the three most frequently mentioned: (1) teachers' knowledge and skills and (2) teachers' attitudes and beliefs.

Although second-order barriers are perceived as relatively persistent over time and resistant to change, researchers provide strategies for overcoming them. A crucial recommendation is that technological innovation must clearly demonstrate its value in the educational process. Fabry and Higgs (1997) point out that the teacher should experience the personal value of technology in increasing the efficiency of instruction. Durff and Carter (2019) explicitly state that *"by recognizing the value of integrating technology, educators were propelled to find ways to overcome any barriers"* (p. 250). Technology should bring a clear vision of how it will enhance teaching and learning and help to reach educational goals (Ertmer, 1999) while building on the subject matter content. In regard to this, Rogers (2000) aptly states that *"technology plans that center on technology rather than teaching and learning create more* *barriers than they prevent"* (p. 469). Finally, a strong recommendation to effectively improve teachers' attitudes towards technology is to support teachers' professional development by discussing and sharing the experience with their peers or mentors (Durff & Carter, 2019; Ertmer, 2015; Ertmer, 1999). This is consistent with the author's own belief that an effective way to convince teachers (both experienced and novice) of the usefulness of a given technology is to present them with very concrete examples of specific activities through someone who has had their own positive teaching experience with them. It seems to me that activities presented "by teachers for teachers" can have a substantially larger impact than materials provided by the manufacturers of teaching aids, no matter how sophisticated they are. In the Czech context, a similar philosophy is represented by the organizers of leading events for physics teachers, such as the traditional annual conference *Physics Teachers' Inventions Fair*, and long-term projects *Elixír do škol* and *Heuréka* (Dvořáková, 2011), which enable informal meetings of hundreds of practising physics teachers both with subject-field didacticians and each other. It is through these events that the meaningful use of technology can permeate school education.

When a new technology finally enters the classroom, the question arises of how students benefit from it. Thousands of researchers around the world are currently working on studies and meta-studies to contribute to answering this question; given the breadth of the issue, they invariably focus on a more narrowly specified context (defined e.g., by the kind of technology, the age of learners, the subject field, the teaching methods, and forms, etc.). In evaluating the effectiveness, usefulness, and learning benefit of a given technology, these studies must deal with the uncontrolled effects highlighted by Clark (1983) in his famous paper – specifically the influence of the instructional method and the *novelty effect*. Although Clark identified the influence of the instructional method as a more fundamental source of bias in research studies, it makes sense to hypothesize that the novelty effect has grown in importance since then, as the attention of our society increasingly requires fleeting attractions and short-term "wow"-effects. The novelty effect manifests itself in the increased effort and attention that students put in lessons spiced up with new technology (Clark, 1983; Elston, 2021). The increased students' engagement can lead to improved performance in the short term; however, when the technology becomes familiar, its attractiveness wears off and the effect of the innovation drops (Clark, 1983; Tsay et al., 2018; Elston, 2021).

In the educational context, the novelty effect has recently often been discussed in relation to gamification (Rodrigues et al., 2022), but almost all technologies providing visually attractive outcomes (in physics e.g., thermal imaging cameras, digital microscopes, 3D printers, augmented and virtual reality, etc.) could possibly be linked with it. Especially if the teacher uses the technology without a clear goal, just to stimulate students' interest with "something nice", there is a real risk it becomes an interesting toy rather than a meaningfully used tool in the long-term view. However, the initial situational interest of students can be exploited if the teacher demonstrates the usefulness of the technology through specific experiments with obvious links to everyday life. Kácovský et al. (2023) showed that it is the perceived value and usefulness of the experimental activity that is a strong predictor of students' intrinsic motivation for practical work.

In any case, realistic expectations towards using new technologies are needed on the part of both teachers and curriculum makers. Technological companies (firstly Gartner, Inc.) have observed and described the so-called *hype cycle*, a sequence of stages that typically accompany the onset of technological innovations in terms of their perceived value and users' expectations (Dedehayir & Steinert, 2016). The cycle (which is effectively no cycle at all) is graphically represented by a curve divided into five phases (e.g., Fenn & Raskino, 2008): the innovation trigger, the peak of inflated expectations, the trough of disillusionment, the slope of enlightenment, and the plateau of productivity (Figure 2.1).

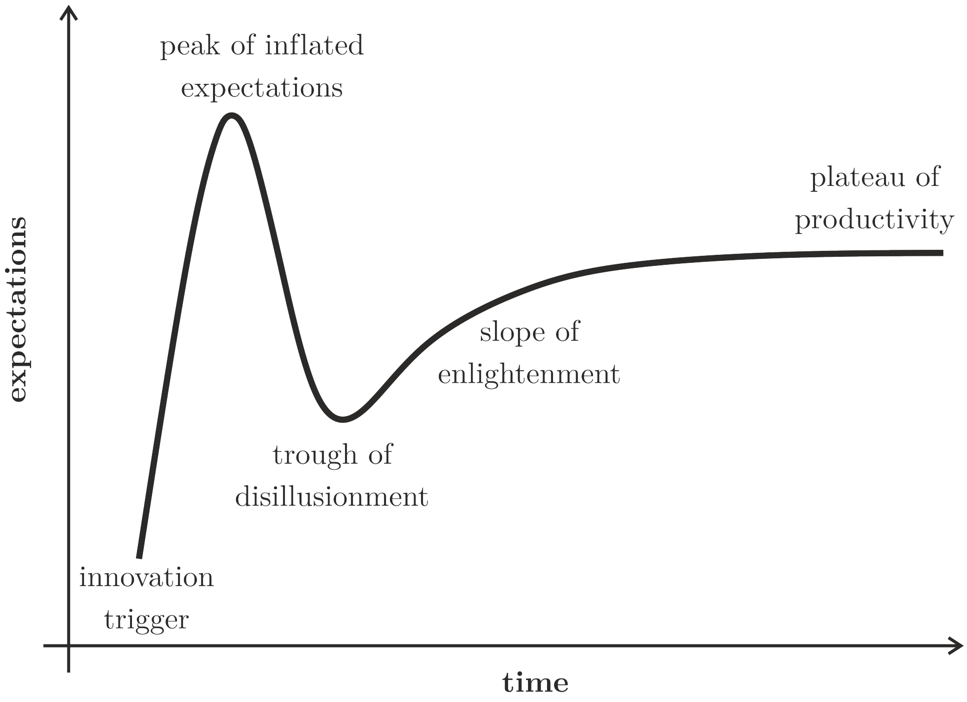

Figure 2.1: Graphical representation of the hype cycle; modified after Fenn and Raskino (2008).

Although the hype cycle primarily predicts the successfulness of a product in the market in time and it is sometimes criticized for overgeneralization and missing scientific framework, the analogy to introducing technologies into education should be noteworthy. Technological waves also hit education, which is associated with high expectations and initial enthusiasm of both teachers and students (see the novelty effect mentioned earlier), after which a phase of disillusionment sets in. And it is also true for education that only in the longer term the best practices and methodologies can emerge to use the technology productively and meaningfully.

Directly in the field of physics education, some researchers are looking at how to foster successful and effective adoption of technology. For example, Planinsic and Etkina (2019) have proposed a framework where they recommend that teachers integrate technology into their lessons in three successive phases. In the first one, students should work with the technology as a black box, in the second one, the aim is to become familiar with how the technology works, and finally, in the third one, students should use the device to learn new physics.

2.2. Thermal imaging: About the technique and the teaching ideas

Infrared thermal imaging (thermography) is a technique to determine the surface temperature of an object by evaluating the electromagnetic radiation emitted by the object surface. Applying the idea of the Stefan-Boltzmann law and knowing the surface properties (such as its emissivity), one can obtain temperature readings even in situations when contact temperature measurements fail (e.g., due to the physical inaccessibility of the surface or a potential danger). Like telescopes or microscopes, thermography broadens the limited ability of our sight when studying the world around us.

Many advantages of thermal imaging are obvious – it is a contactless, non-invasive approach that does not influence the measured sample in any way. Instead of just point temperature information gained by usual temperature sensors, thermography provides a 2D temperature field depicted in false colours (a thermogram) and enables to study its changes in real time. The visual feedback provided is immediate, which is why Haglund et al. (2016) refer to simple thermal imaging activities as *instant inquiry***.** It is also very important that such inquiry is intuitive – recently published studies show that even for children as young as 10 years, it is easy to operate a thermal imaging camera and interpret false colour pictures correctly (Haglund et al., 2016).

Thermal imaging in science education

Thermal imaging was initially developed as a technology for military purposes. When it became available also for civilian use in the 1990s, it was clear that thanks to its advantages mentioned above, it would also penetrate (science) education over time. The paper *There is more to see than eyes can detect* published by Vollmer et al. (2001) can be seen as visionary, showing several applications of thermal imaging cameras in physics teaching and predicting a future boom of thermal imaging in education. Möllmann and Vollmer (2007) then expanded the palette of the original proposals a few years later with additional experiments oriented at undergraduate students and described the underlying physics theory as well. In 2010, the same authors published the book *Infrared Thermal Imaging: Fundamentals, Research and Applications* with an entire chapter of almost 50 pages devoted to the use of thermal imaging cameras in physics teaching (Vollmer & Möllmann, 2010). This moment opened the imaginary "golden decade" of thermal imaging in education, during which many teaching ideas were proposed on how to integrate thermal imaging into science education (i.e., besides physics also into biology, chemistry, or environmental education). A certain culmination of these efforts is the recently published book *Thermal Cameras in Science Education* (Haglund et al., 2022), which provides an overview of what happened in education-oriented thermal imaging mainly in the past decade.

The gradual introduction of thermal imaging cameras into teaching has undoubtedly been helped by the falling prices of infrared cameras. This continuous trend, which after 2010 involved handheld cameras, accelerated significantly around the middle of the last decade when simple thermal imaging cameras appeared on the market in the form of smartphone accessories.

These add-ons turning a tablet or smartphone into a thermal imaging device brought a small revolution – the price drop that came with their rise allowed many schools to purchase more than one device and thus incorporate thermal imaging cameras into lab work in small student groups. As the apps controlling these cameras are usually freely available, students can also use them on their smart devices, making thermal imaging part of the BYOD – *bring your own device* – approach. This approach takes advantage of students' close affinity to their smart devices, and research has already confirmed that it can be effective in increasing student engagement and interest in school activities (González et al., 2015; Hochberg et al., 2018; Wijtmans et al., 2014).

Of course, we have to admit that usually being at the lowest price level on the market, thermal imaging cameras used in schools have obvious limits. These certainly include limited screen resolution and limited options of more advanced settings (including e.g. only discrete values of emissivity available or the missing option of choosing the reflected temperature); in addition to that, their refresh rate is quite low, especially in the case of smartphone accessories. On the other hand, in most experiments in science education, precise quantitative results do not matter – on the contrary, we often work with temperature differences or time evolution of the temperature field rather than with absolute temperature readings.

The following sections provide a brief overview of what activities employing thermal imaging cameras have been proposed and published in recent years. The vast majority of these activities is designed for the secondary school level (lower or upper), with experiments intended for undergraduate students being rather rare; however, even these can usually be accompanied by comments in a way that they can be used even with younger students.

Teaching ideas in biology and chemistry education

In biology, animals, plants, and humans can be used as subjects of study. In the case of fur-bearing animals, for example, the authors (e.g., Wong & Subramaniam, 2020a) suggest investigating the insulating properties of the fur (which usually prevents direct measurement of the skin temperature). In Haglund et al. (2022), a whole chapter is devoted to exploring the temperature of different parts of animal bodies (e.g., horses' legs, rabbits' ears) and to investigating how a thermal imaging camera can help students to grasp thermal regulation in animals. Thermal imaging also gives a unique opportunity to investigate cold-blooded animals such as crickets (Short, 2012) or frogs (Wong & Subramaniam, 2020b) without physical contact with them; Unger et al. (2020) suggested a comprehensive teaching sequence on studying endotherms and ectotherms. Similarly, Xie (2012) describes studying the thermogenesis of a moth, although one may question the extent to which such a phenomenon is observable under usual school conditions. Thermogenic behaviour could also be observed in some plants (Wong & Subramaniam, 2020a). As for plants, capillary actions could be modelled by simple aids and then observed by thermal imaging – Xie (2012) suggests comparing freshwater and saltwater.

Of course, there are also many interesting things to explore about the human body. Cameras used in teaching are usually not of a quality that can detect elevated temperature associated with inflammation (such as those used for instance in rheumatology), but they are able to visualise temperature changes on the nasal mucosa during inhalation and exhalation (Vollmer & Möllmann, 2018). Furthermore, temperature changes on peripheral parts of the human body – e.g., palms (Wong & Subramaniam, 2020a) or fingers (Wong & Subramaniam, 2020b) – could be studied.

Proposals published in the field of chemistry education involve the study of many different chemical processes but nearly always, thermal imaging cameras are used to monitor temperature changes in chemical reactions to decide whether heat is released or absorbed. Exothermic reactions that have been proposed by the authors of published articles include the dilution of sulfuric acid or ethanol in water (Xu et al., 2019), neutralization (Bohrmann-Linde & Kleefeld, 2019), or crystallization of sodium ethanoate trihydrate, which is used in commercially available heat packs (Wong & Subramaniam, 2020b); endothermic processes are usually focused on the dissolution of common substances, such as sodium chloride, baking soda, or D-glucose (Bohrmann-Linde & Kleefeld, 2019; Short, 2012; Wong & Subramaniam, 2020b; Xie, 2011, 2012).

Another group of ideas focuses on vapour pressure lowering and demonstrating Raoult's law (Xie, 2011, 2012; Xu et al., 2019). Measurable thermal phenomena are also accompanied by spectacular chemical experiments, such as spontaneous smoldering of fine metal powder (Xu et al., 2019), production of cold light (Bohrmann-Linde & Kleefeld, 2019), or playing with dry ice (Short, 2012).

Teaching ideas in physics education

Among school subjects, physics inherently offers the greatest potential for the use of thermal imaging cameras and is therefore also the field with the most published literature available. Unsurprisingly, most of the activities worthy of attention fall thematically within the field of thermal physics, which mainly deals with energy transformations and temperature changes. This area is also considered to be conceptually challenging because it is where students' naive beliefs about everyday thermal phenomena clash with correct scientific explanations. Therefore, the ambition of many authors is to design experiments that would induce a cognitive conflict between the real observed phenomenon and students' misconception, which would make the student reconsider his/her beliefs and lean towards the scientifically correct justification. Research examining the extent to which this approach is effective will be discussed in Section 2.3; here again, we will only focus on a brief overview of teaching ideas provided in the literature.

Because thermal cameras significantly outperform contact thermometers in measuring the surface temperature of objects, they are a suitable tool for studying thermal conductivity. Therefore, probably the most popular experiment ever performed with thermal cameras is the comparison of the thermal conductivity of a good conductor (typically metal) and a good insulator (wood, plastic, cardboard, etc.), described in various variations (Haglund et al., 2016; Haglund et al., 2017; Kácovský, 2018; Short, 2012; Schönborn et al., 2014; Vollmer et al., 2001; Xie & Hazzard, 2011). This experimental situation also received the most research attention, as described in Section 2.3.

Thermal cameras have also proved useful in studying other ways of heat transfer – convection and radiation. In the case of convection, it is possible to study both the motions inside liquids (Kácovský, 2019b; Möllmann & Vollmer, 2007; Vollmer & Möllmann, 2017; Vollmer & Möllmann, 2010) and the motions of air masses (Xie, 2012); Kácovský (2018) also proposes to observe convection of a protective inert gas inside a light bulb. In the case of radiation, thermal imaging provides a unique opportunity to investigate the properties of far-infrared radiation and compare them to those of visible light. It is possible to observe transmission through different materials, often plastic films or glass (Kácovský, 2019b; Melander et al., 2016; Vollmer & Möllmann, 2017, 2018; Vollmer et al., 2001; Vollmer & Möllmann, 2010; Wong & Subramaniam, 2018a, 2020b) or reflected radiation (Kácovský, 2018; Möllmann & Vollmer, 2007; Wong & Subramaniam, 2018a), whose presence in the scene can be confusing for students. A standard experiment to make students aware of the importance of emissivity (especially the very low emissivity of polished surfaces) is the use of a Leslie cube that is either heated electrically or with hot water (Haglund et al., 2017; Melander et al., 2016; Vollmer & Möllmann, 2010). An interesting experiment is one in which paper printed with different coloured stripes is exposed to sunlight and a thermal imaging camera measures the temperature rise on the individual stripes (Xie, 2012).

Like thermal conductivity, a conceptually difficult area of thermal physics are phase transitions. Thermal cameras, which have the aforementioned advantage of convenient surface temperature measurements, allow easy observation of the evaporative cooling effect (Möllmann & Vollmer, 2007; Vollmer & Möllmann, 2010), including the comparison of its intensity for different liquids, such as water and ethanol (Kácovský, 2018). Very remarkable are experiments that simultaneously show the absorbing latent heat due to evaporation and the subsequent release of latent heat through the instantaneous condensation of the resulting vapour on a hydrophilic surface (Samuelsson et al., 2019; Xie, 2011, 2012; Xie & Hazzard, 2011).

Another common use of thermal imaging cameras is to visualize frictional heating (Haglund et al., 2015a, 2015b; Kácovský, 2019b; Vollmer & Möllmann, 2017, 2018; Vollmer et al., 2001; Vollmer & Möllmann, 2010; Wong & Subramaniam, 2020b), but this concept is usually familiar to students and expected by them. Much more surprising to them is that objects warm up in inelastic collisions, where part of the mechanical energy is converted into internal energy of the interacting bodies. This phenomenon can be demonstrated, for example, when a ball hits the ground (Haglund et al., 2015b; Kácovský, 2019b; Vollmer & Möllmann, 2017) or a hammer or mallet hits an insulating board (Kácovský, 2018). Students often mistakenly attribute the temperature rise observed when different bodies come into inelastic contact to sliding friction (Kácovský, 2019b), although no sliding is present – this makes these experiments a suitable introduction to the concept of internal energy (and the first law of thermodynamics).

Thermal imaging cameras can also be used in experiments in electricity and magnetism where significant temperature changes occur. Traditionally, experiments showing energy dissipation in resistors connected once in parallel and twice in series have been described in this field (Kácovský, 2018; Netzell et al., 2017; Vollmer & Möllmann, 2010; Wong & Subramaniam, 2018b, 2020b); more complicated DC circuits allow, for example, the verification of Kirchhoff's current law (Kácovský, 2019a). With an AC generator that can produce very low-frequency signal (around 1 Hz), it is also possible to study power oscillations in AC circuits (Kácovský, 2019a). An interesting link between thermal physics and electricity can be found when exploring the temperature rise of a resistor as a function of its specific heat capacity (Kácovský, 2019a). A truly original and aesthetically interesting experiment is the use of a thermal imaging camera to solve a maze created by an electrically conducting material, as suggested by Ayrinhac (2014). In addition to effects in a closed electrical circuit, one can also find topics related to thermoelectric phenomena, i.e., the Seebeck and Peltier effect (Möllmann & Vollmer, 2007; Vollmer et al., 2001; Vollmer & Möllmann, 2010), and to eddy currents (Vollmer & Möllmann, 2010).

Finally, let us mention ideas for experiments that are not directly related to school physics but have teaching potential or provide insight into practical everyday applications. We can mention, for example, the visualization of heat pump operation (Haglund et al., 2017; Melander et al., 2016), the investigation of hidden structures in building thermography (thermal bridges, energy efficiency) (Möllmann & Vollmer, 2007; Short, 2012; Vollmer & Möllmann, 2017; Vollmer et al., 2001; Xie & Hazzard, 2011), the simulations of the greenhouse effect (Xie, 2012) or the blower-door test (Xie & Hazzard, 2011), or the observation of the temperature distributions inside a microwave oven (Vollmer & Möllmann, 2010) or in the Joule-Thomson experiment (Haglund et al., 2017; Melander et al., 2016). Finally, even a common commercially available thermal camera can be used to measure the temperature of the Moon (Vollmer & Möllmann, 2017; Vollmer et al., 2011; Vollmer & Möllmann, 2012).

Of course, inspiring experiments with thermal imaging cameras can also be found freely on the web – the leading source is the website *InfraredTube* (The Concord Consortium, n.d.) created by Charles Xie.

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The long list of suggestions above shows that even physics educators and idea makers themselves find the topic of thermal imaging very attractive. However, since many ideas are already beginning to be duplicated, it can be expected that the number of new ones will diminish in this decade and more attention will be given to research on how to use thermal imaging cameras effectively and to the students' maximum benefit. In the terminology of the hype cycle mentioned earlier, the use of thermal imaging cameras probably gradually enters a phase referred to as the "plateau of productivity". However, the first research on the meaningful and effective use of thermal imaging cameras has already been published and is the focus of the following section.

2.3. Physics education research on activities using thermal imaging cameras

As already mentioned in the previous section, thermal physics is a conceptually very rich area that is phenomenologically concerned with macroscopic phenomena whose explanations, however, lie in the microscopic description. Moreover, if we consider that thermal phenomena are intuitive and familiar for all of us from early childhood, the students' reasoning about thermal physics is highly prone to misconceptions.

Over the past decades, many studies (e.g., Alwan, 2011; Erickson, 1979; Erickson & Tiberghien, 1985; Harrison et al., 1999; Leinonen et al., 2013; Lewis & Linn, 1994) were published that identified these misconceptions, described them in detail and concluded that they are often robust, in many cases age-independent and resilient to change. To provide a basic overview, below is a slightly modified list of misconceptions in thermal physics as organized by Kácovský (2015) based on previously published literature (see Table 2.1).

Table 2.1: Common misconceptions in thermal physics; adapted from Kácovský (2015).

Topic	Common misconceptions
Heat	There is something like "hot heat" and "cold heat" (heat vs. cold). Heat is a material substance. Heat is proportional to temperature. Heat rises. / Heat travels upwards. Heat and cold flow like liquids. An object can "own" a certain amount of heat.
Temperature	Temperature is an extensive quantity, while heat is an intensive quantity. Temperature is the measure (the amount) of heat. The temperature of boiling water can exceed 100 °C during boiling. The temperature of an object depends on its size. The temperature will change during melting or boiling.
Heat conductivity, thermal equilibrium	Metals attract, hold, or store heat and cold. Wool warms things up. Skin or touch can determine temperature. Some substances (e.g., metals) are naturally colder than others (e.g., wood). The temperature of different objects is different even though they have been in the same room for a long time.

Experience has shown that some efforts to face students' misconceptions have only marginal results, and research is therefore always looking for new, more effective ways. In Sweden, a group of researchers has formed around Professor Jesper Haglund, recognising the potential of thermal imaging cameras and focusing on their possible use in eliminating students' misconceptions by visualizing heat transfer. At present, their work, which I will discuss in the following paragraphs, is the most extensive of its kind. Although due to intuitive handling, technologies like thermal imaging cameras are considered to be suitable for open-ended, inquiry-based experimental assignments (Haglund et al., 2017; Melander et al., 2016; Xie & Hazzard, 2011), almost all practical work activities described in the research papers follow the more guided inquiry – the POE approach (see Section 1.2).

The first study published by the team (Schönborn et al., 2014) involved eight 7th graders with no previous school experience with thermal physics. Handling a piece of metal (a knife) and a piece of wood and following POE instructions, the pupils were expected to experience a cognitive conflict when comparing their tactile sensation (the "coldness" of the metal) with thermal images obtained in real time. The cognitive conflict did occur, but the pupils were not able to resolve it, because they did not come up with the idea of an energy flow from their hands to the metal. The authors, therefore, recommend combining a carefully designed thermal imaging sequence with an explicit introduction of a macroscopic heat flow model.

The next study by Haglund et al. (2015a) involved upper secondary students and was not focused on misconceptions themselves, but on students' conceptual and epistemological framing of activities with thermal imaging cameras. The authors worked with a class of thirty 11th graders rotating in small groups between four laboratory stations that were aimed at thermal conductivity and dissipative processes (inelastic collisions, friction). Analysing the videotaped practical work of a group of three students, the combination of thermal imaging and POE was found *„to allow the students to justify their assertions in the basis of the scientific evidence"* (p.18). The authors found that upper secondary school students (17–18 years old) often used microscopic explanations to justify the above experiments. Further, they struggled with interpreting "strange" temperature readings caused by reflections on shiny surfaces. While the paper suggests (albeit not explicitly) that students do not have much problem with reasoning about dissipative processes, the issue of thermal conductivity was more difficult. The experiment in question was designed exactly the same as it is described in Schönborn et al. (2014), i.e., students were expected to touch metal and wooden pieces of material and compare their tactile feeling with an IR image. Authors admit that students were *"not comfortable with the observed outcome (…) even at the end of the exercise"* (p. 19), still being convinced that *"if something feels cold, it must be cold"* (p. 19). In this context, let me recall the famous book *Children's ideas in science*, where Erickson, in a passage devoted to misconceptions in thermal physics, states: *"If pupils were able to see this phenomenon [that metal feels colder than wood] in terms of transfer of energy from their body to the object, this sort of situation would likely be less of a problem than it seems to be at present…"* (Erickson & Tiberghien, 1985, p. 59). The above results show that even though the present thermal imaging technique actually enables "seeing" the heat flow, the shift in students' minds is not guaranteed. To help students overcome the misconception, the authors suggest also using a microscopic model of thermal conduction or introducing students to some tactile illusions, so they stop relying on their hands as trustworthy thermometers.

One year later, Haglund et al. (2016) published a narrative analysis of the potential of using thermal imaging cameras in developing concepts such as heat, temperature, thermal equilibrium, or thermal conduction. The study captures the experience of five 4th graders (9 to

11 years old) who worked on four POE-designed experimental activities within three weeks. The first activity introduced pupils to the functioning of thermal imaging cameras, and the second one to the macroscopic heat-flow model. The third activity involved small-group practical work, where pupils encountered three experiments, more specifically (1) the iconic, already mentioned experiment with the thermal conductivity of a knife and a piece of wood (described earlier, see Haglund et al. (2015a) or Schönborn et al. (2014)), (2) tactile illusions (proposed by Haglund et al. (2015a), see above) and (3) insulating properties of some materials. The fourth activity was a demonstration aimed at the thermal conductivity of a metal. A look at the above research scheme suggests that the authors applied their own recommendations proposed by Haglund et al. (2015a). Authors conclude that the 4th graders successfully adopted the heat-flow model when explaining their experimental results, even those related to thermal conduction – which was not true for students from previous studies (Haglund et al., 2015a; Schönborn et al., 2014), where the explicit macroscopic introduction of the heat-flow model was missing. This is consistent with Abrahams and Millar (2008) who stress that concepts must first be introduced to learners, and one cannot rely on these somehow “emerging” in their minds during practical work.

The results of the three above-mentioned studies were then summarised at an informative level by Haglund et al. (2015b, 2016). In these papers, the authors state that simple practical work with thermal imaging cameras can support a conceptual understanding of thermal physics; however, it must be supplemented by introducing age-appropriate explanatory models at the microscopic and/or macroscopic level. An example of a conceptually challenging area where mere observation of processes with a thermal imaging camera does not automatically lead to an understanding of the physics essence is thermal conductivity and the associated tactile feelings; as stated by Haglund et al. (2015b), *“students do not see what they are not yet able to see“* (p. 428).

The Swedish research team also targeted undergraduate physics students by looking at how they work with thermal imaging cameras in an open-ended investigation on thermal radiation (Haglund et al., 2017). The results of this interpretive study suggest that while secondary school students use thermal imaging cameras like thermometers (i.e., they usually primarily “watch numbers” = temperature readings), undergraduate students take it as a tool to explore infrared radiation itself – including thermal reflections and the issue of emissivity.

The most recent research by Samuelsson et al. (2019) focused on the issue of phase transitions, specifically on temperature changes during evaporation and condensation. A group of pre-service teacher students was exposed to three practical work episodes involving thermal imaging, namely (1) walking out of a shower, (2) sitting in a sauna, (3) condensation on and evaporation from a paper placed over a cup of water (proposed by Xie (2011)). It was this third experiment that proved to be crucial, because only after its completion the students were able to provide a consistent explanation for the temperature drop they observed due to evaporative cooling. However, as the authors stated, *“the idea that energy is required for evaporation and released during condensation was not central to their line of reasoning”* (p. 581). This is why a coherent justification of evaporation and condensation together was not provided since students explained condensation in terms of heat exchange from the warmer water vapour to the colder paper accompanied by phase transition. In other words, they perceived condensation as a concomitant effect, not a true cause of temperature changes. The authors concluded that students do not take into account that energy is released when bonds are formed during condensation so instead, they provided an explanation referring to the second law of thermodynamics (spontaneous heat transfer from a hotter to a colder object).

As for other research, the question *"how students and instructors, investigating thermal phenomena with IR cameras, come to conceptually and epistemologically frame the naturalistic setting they participate in"* (p. 2) is a focal point of the licentiate dissertation of Samuelsson (2020). I would also like to mention the earlier notable work of Atkins et al. (2009) who investigated how visitors interact with a thermal imaging camera placed in a science museum; the authors found that the opportunity to work with the camera with almost no guidance makes visitors act more creatively than providing them with detailed instructions.

The studies whose results were summarised in this section were mainly those focusing on understanding thermal phenomena. However, other research not directly related to physics concepts has also been published. For example, Loukomies et al. (2022) examined the emotions of twenty-four 5th graders related to practical work with thermal imaging cameras. Their results show that positive emotions significantly outweigh negative ones (such as boredom); however, the pupils most often described the activities vaguely as being simply "nice"; three respondents expressed (situational) interest in them. Wessnigk and Haase (2020) focused directly on the potential of infrared cameras in developing situational interest in 7th graders working with them for three class periods. The pupils were emotionally engaged in the thermal imaging activities and appreciated that they can "see the invisible"; however, no change in the current interest level was found. On the other hand, the pupils highly valued the practical work itself, thus, as the authors admit, pupils' interest might be individual (i.e., stable in a short term) rather than only situational.

At the primary level, thermal imaging activities were also investigated in terms of the dialogue between pupils and the teacher (Åhman & Jeppsson, 2022). The infrared cameras were found to capture pupils' focus on the experiments and to provide graphical outcomes that help pupils *"place words on abstract science phenomena [such as heat] in a coherent and adequate way"* (p. 108).

2.4. Original papers on the topic

1) Kácovský, P. (2018). Thermal Imaging Experiments as an Inspiration for Problem-based Learning. *The Physics Teacher*, *56*(9), 596–599.

2) Kácovský, P. (2019). Electric Circuits as Seen by Thermal Imaging Cameras. *The Physics Teacher*, *57*(9), 597–599.

3) Kácovský, P. (2019). The visit of a thermal imaging world in one physics lesson. *Physics Education*, *54*(4), 045011.

4) Kácovský, P. (2021). Studying the Rate of Evaporation Using Pocket and Computer-Supported Weighing Scales. *The Physics Teacher*, *59*(6), 493–496.

Paper:

Thermal Imaging Experiments as an Inspiration for Problem-based Learning

Author: Petr Kácovský

Published in the *The Physics Teacher*, Volume 56, Issue 9, 2018, pp. 596–599.

DOI: 10.1119/1.5080571

Impact Factor (2018) = 0.638

Paper:

Electric Circuits as Seen by Thermal Imaging Cameras

Author: Petr Kácovský

Published in the *The Physics Teacher*, Volume 57, Issue 9, 2019, pp. 597–599.

DOI: 10.1119/1.5135785

Impact Factor (2019) = 0.671

Paper:

The visit of a thermal imaging world in one physics lesson

Author: Petr Kácovský

Published in the *Physics Education*, Volume 54, Issue 4, 2019, article no. 045011.

DOI: 10.1088/1361-6552/ab15b9

No Impact Factor

Paper:

Studying the Rate of Evaporation Using Pocket and Computer-Supported Weighing Scales

Author: Petr Kácovský

Published in the *The Physics Teacher*, Volume 59, Issue 6, 2021, pp. 493–496.

DOI: 10.1119/10.0006140

Impact Factor (2021) = 0.566

2.5. Note on related work

At this point, I consider it necessary to emphasise that the papers mentioned above are only a part of my work on the development of experimental activities at the upper secondary level and methodical materials related to them. Much of my efforts focus on materials intended for Czech audiences – students, but mainly teachers. The texts are written in the Czech language and freely available online, which is what the teachers need – however, such kinds of materials have only negligible potential to be published in impact factor journals. Nevertheless, I consider creative contributions to the benefit of the local teachers' community to be a very important part of my work, a kind of a natural mission. Below is a brief summary of larger projects that focus on developing materials for local teachers/students and that I am involved in; my role and the extent of my work are also provided.

Project: Collection of Physics Experiments [Sbírka fyzikálních pokusů]
About the project: an online collection of experiments aimed at secondary teachers
My role: head of the collection, author of ca. 60 experiments (texts for teachers, videos)
URL: http://fyzikalnipokusy.cz

Project: Cookbook of simple experiments [Kuchařka jednoduchých experimentů]
About the project: an online database of experiments using Vernier sensors, teacher-oriented
My role: co-author of ca. 105 experiments (texts for science teachers)
URL: https://www.vernier.cz/experimenty/kucharka

Project: Interactive Physics Laboratory [Interaktivní fyzikální laboratoř]
About the project: a laboratory aimed at upper secondary students' independent practical work
My role: head of the laboratory, author of ca. 30 experimental stations (student worksheets)
URL: https://www.mff.cuni.cz/cs/kdf/akce-pro-zaky-zs-a-ss/interaktivni-fyzikalni-laborator

Project: Videoanalysis [Videoanalýza]
About the project: experiments using Tracker software in teaching mechanics, teacher-oriented
My role: author of 12 activities (texts for teachers, student worksheets, videos)
URL: http://kdf.mff.cuni.cz/~kacovsky/videoanalyza.php

3. Students' intrinsic motivation towards experiments in physics

Chapter 2 was devoted to designing experimental activities and discussing their contribution to conceptual understanding. In my own experience, however, in some situations, the gain of learners' understanding is difficult to measure. This is particularly the case of one-off learning events, such as physics performances or hands-on workshops organized for upper secondary students that both represent a significant part of my work as an educator. In this role, I encounter hundreds of upper secondary students each year about whom I have little or no information in advance. Prior to the one-off intervention, I have no idea about their progress in regular physics lessons, I do not know what their teacher emphasizes, and I have no opportunity to administer any kind of pre-test or set up an experimental and control group. Under these circumstances, it is difficult to infer any shift in students' understanding.

However, it is a natural need of any educator to get relevant feedback from students on his/her teaching. Thus, if direct evaluation of the intervention's learning gain is impossible, it seems reasonable to measure different effects of the intervention that serve as learning gain predictors. Undoubtedly, such important predictors are students' intrinsic motivation and interest, whose development has been proven to lead to better performance (see Section 3.3). When we measure intrinsic motivation or interest, we obviously do not get straightforward information about what we have specifically taught students, but in simpler terms, the results will indicate whether our intervention has made some students more likely to engage with our subject area and, as a result, learn more in it by their own choice. This idea is shown in Figure 3.1.

It is the issues of intrinsic motivation, interest, and their measurement that have become my main research interest since 2016. This chapter of my thesis is devoted to this topic, which provides a theoretical background for the publications listed in Section 3.6.

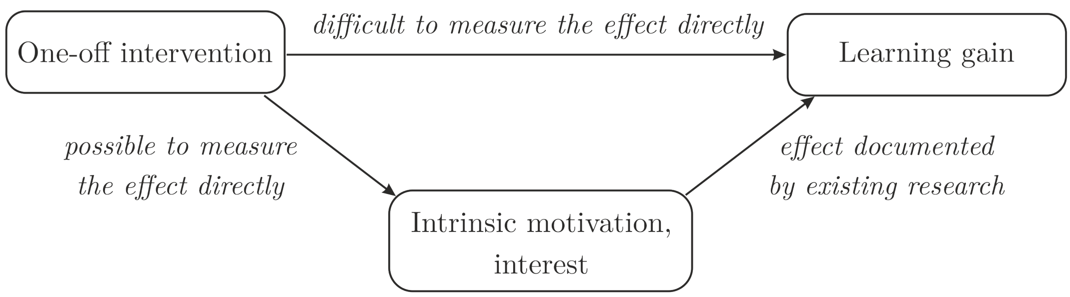

Figure 3.1. The support for intrinsic motivation measurements in one-off interventions.

3.1. Intrinsic motivation through the lens of self-determination theory

Motivation (from Latin: *movere* = to move) is a psychological term on whose definition there is a lack of consensus. However, many definitions are intertwined with that of Elliot and Zahn (2008) who refer to motivation as *"energization and direction of behaviour"* (p. 687) – as such, it will also be understood within this thesis. From the perspective of educational psychology, motivation is a fundamental concept as it determines the behaviour and actions of students and teachers during the educational process. It is therefore not surprising that there are many theoretical frameworks that attempt to explain the nature and mechanisms of human motivation and different types of motivation have been classified according to different criteria. Probably the most common classification used today is distinguishing between *intrinsic* and *extrinsic motivation.*

Intrinsically motivated people do an activity for their own inherent satisfaction, for their own interest and enjoyment, without being driven by external incentives (so-called free-choice behaviour). On the other hand, extrinsically motivated behaviour is such where explicit external stimulating factors can be found, such as rewards or threats. Distinguishing between intrinsic and extrinsic motivation is, however, difficult in some situations – if external incentives are not apparent, but hidden or distant (e.g., distant in time), there is a risk of misleadingly attributing an individual's behaviour to his/her intrinsic motivation. Similarly, it is not uncommon for behaviour that was initially externally motivated (e.g., working for a good salary) to become intrinsically motivated over time (if the work brings intrinsic satisfaction that far exceeds the subjectively perceived value of the money) – in this case, we are talking about so-called internalized extrinsic motivation.

The term intrinsic motivation was probably first used in the 1950s by Harry F. Harlow in reference to some features of primate behaviour that did not appear to be motivated by extrinsic incentives (Harlow, 1950). In the second half of the 20th century, it gradually became apparent that the role of intrinsic motivation was also more fundamental in explaining human behaviour than originally expected. What became one of the most prominent frameworks for the relationship between extrinsic and intrinsic motivation was the *cognitive evaluation theory* (CET) proposed during the 1970s (Deci, 1975). The crucial concepts of the CET are two humans' psychological needs – *competence*, i.e., the need to feel effectiveness and mastery, and *autonomy*, the need to self-regulate one's behaviour (Ryan & Deci, 2017); both these needs are necessary to maintain intrinsic motivation. In other words, events strengthening feelings of competence and autonomy support intrinsic motivation, and events weakening these feelings undermine it.

The CET puts a strong focus on the effect of extrinsic rewards on intrinsic motivation. Rewards are basically divided into two groups, tangible and verbal. Tangible (incl. monetary) rewards have been shown to undermine intrinsic motivation, if they are promised in advance, before the task, but if they come unexpectedly, they do not affect intrinsic motivation (Cameron & Pierce, 1994, Deci, 1971, Ryan & Deci, 2017). Verbal rewards (praises) and positive non-controlling feedback are considered to generally increase intrinsic motivation

(Cameron & Pierce, 1994, Deci et al., 1999, Ryan & Deci, 2017). However, both sorts of rewards can have a negative impact on intrinsic motivation if they are overly salient and one gets the feeling that their purpose is to control, to direct his/her behaviour (Deci et al., 1999, Ryan & Deci, 2017). This feeling of being externally controlled (as well as being punished or surveilled) undermines the feeling of autonomy, which, as mentioned above, is one of the prerequisites of intrinsic motivation. Rewards could be also harmful to intrinsic motivation if they are promised but not provided, if they are offered too authoritatively or if they omit one's individuality (Cameron & Pierce, 2008).

At this point, let me point out that in the educational setting, the CET describes the effect of rewards provided in the context of performance-contingent tasks as generally negative, while some competing theories (such as the social cognitive theory by Bandura (1986)) value it as positive. The results of the extensive meta-analysis by Cameron and Pierce (1994) lean more towards the latter position, concluding that intrinsic motivation is fostered by those rewards that are related to achieving a certain level of performance. In addition, the authors report that in tasks with low initial interest, any rewards can have a positive impact on intrinsic motivation.

Over time, other theories addressing aspects of personality development and human behaviour began to complement the CET, always extending the existing body of knowledge. Thus, thanks to the American psychologists Edward L. Deci and Richard M. Ryan, an empirically based metatheory known as *self-determination theory (SDT)* was gradually born (Deci & Ryan, 1985; Ryan & Deci, 2000). The SDT started with a narrow focus on intrinsic motivation (CET) but has gradually grown, pointing out the importance of social contexts for intrinsic motivation. Among other topics, it also brings a new perspective on well-being, life goals, relationship quality, etc. (Ryan & Deci, 2019). The SDT is currently made up of six mini-theories that are briefly summarized in Figure 3.2.

As the focus of the SDT has expanded to include social conditions for the development of intrinsic motivation, the two basic psychological needs emphasized by the CET, competence and autonomy, have been supplemented by a third one – *relatedness*, i.e., the need to feel socially connected (Ryan & Deci, 2017). Together, competence, autonomy and relatedness represent the framework of fundamental psychological needs accented in the SDT.

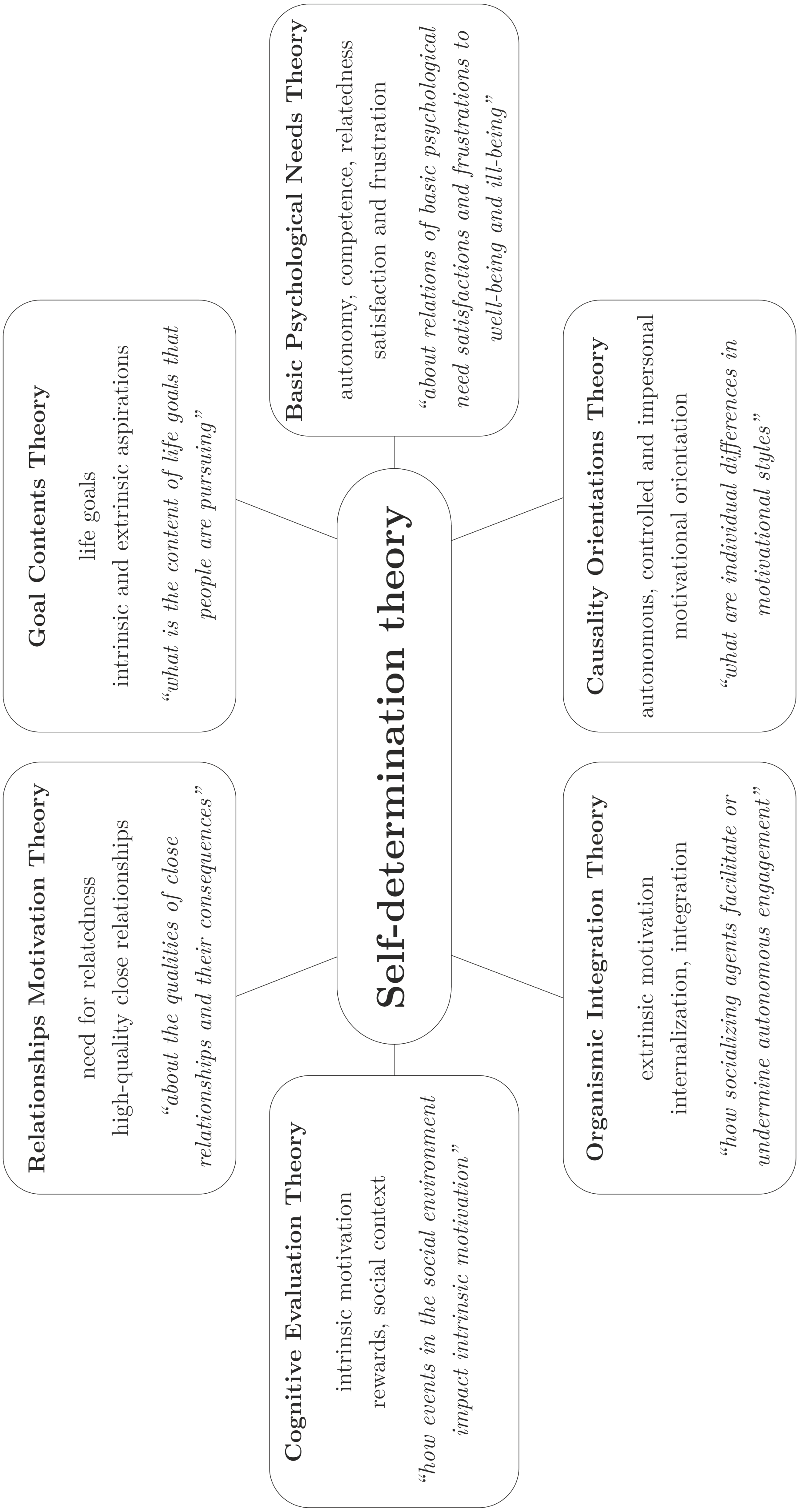

Figure 3.2. The overview of six mini-theories of the SDT – for every mini-theory, its key concepts and focus are listed (in italics); compiled from: Ryan and Deci (2017), Ryan and Deci (2019).

3.2. Interest and its development

Texts on intrinsic motivation often mention the concept of interest or intrinsic interest. As some researchers (O'Keefe et al., 2017; Reeve, 1989) have pointed out, the terms intrinsic motivation and interest are sometimes used completely or almost interchangeably, but many authors try to distinguish between them.

The ways in which interest is conceptualised are not uniform. Some researchers conceive it as a psychological state, an individual disposition (Hidi, 2000; Hidi & Renninger, 2006) or as *"one of a set of motives that may result in intrinsically motivated behaviour"* (Hidi, 2000, p. 316). Krapp (1999, 2007) is a proponent of the so-called *person-object theory of interest* that conceptualizes interest as an enduring relationship, an interplay between a person and an object, and not solely the disposition of a person. Other authors (Reeve, 1989; Schiefele, 2009; Silvia, 2006) tend to describe interest as an emotion underlying intrinsic motivation, pointing out that psychological state is vaguely defined (Schiefele, 2009); the latter approach is also preferred in this text. An overview of different conceptualizations of interest is provided by Renninger and Hidi (2011).

In relation to intrinsic motivation, interest tends to be seen as a less general concept (Guthrie & Wigfield, 1999), as an implicit aspect of intrinsic motivation (Deci, 1992), its precondition (Hidi & Harackiewicz, 2000) or antecedent (Schiefele, 2009). Reeve (1989) proposed that interest is one of two drivers of intrinsic motivation, the other being enjoyment; while interest contributes to initiating and focusing attention on some activity, enjoyment maintains the determination to sustain it, to persist. All these approaches show that the link between intrinsic motivation and interest is very close. This is essential if we want to measure intrinsic motivation – as Hidi (2000) states, in psychological measurements the participants' expressed interest is considered a straightforward measure of intrinsic motivation.

It turns out that the development of interest over time typically has two characteristic phases, situational and individual interest. Situational interest is usually a temporary affective reaction generated by specific tasks, situations and objects that catch one's attention (Hidi, 2000; Hidi & Renninger, 2006; Schiefele, 2009). On the other hand, individual interest is a relatively stable, enduring orientation towards certain activities or subject areas (Schiefele, 2009). It is well-documented that repeatedly experienced situational interest can – through the development of positive values and feelings over time – lead to increased levels of long-term individual interest (Harackiewicz et al., 2016; Hidi, 2000; Palmer et al., 2016; Schiefele, 2009).

As the theory of both intrinsic motivation and interest has been further elaborated, more detailed models of interest development have been proposed, assuming that both situational and individual interest are themselves further composed of certain stages. A certain culmination of these findings is the formulation of a four-stage model of interest development (Hidi & Renninger, 2006), which is shown in Figure 3.3. According to the authors, situational interest has a phase of triggering marked by a short-term increase in attention, and a subsequent phase of maintaining where attention persists focused for a longer time. Emerging individual interest represents the phase where one intentionally begins to seek repeated engagement in certain activities based on more enduring predispositions; in the case of well-developed interest, the goal-directed behaviour is established. As Figure 3.3 suggests, earlier phases of interest may be preconditions for higher levels of interest development.

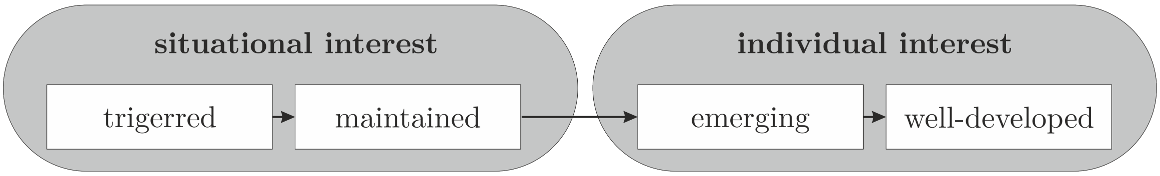

Figure 3.3. Four phases of interest development as suggested by Hidi and Renninger (2006).

However, it turns out that interest development probably does not have to be a linear process as just described. For example, Figure 3.3 suggests that only maintained situational interest could lead to the birth of individual interest as stated by Hidi and Renninger (2006) – in other words, that triggered situational interest is not sufficient for this. However, for example Schiefele (2009) states that the development of individual interest could be supported by both triggered and maintained situational interest, i.e., in two separate ways. Similarly, some authors note that if individual interest is already developed, then it usually contributes to situational interest when novel, object-of-interest-related stimuli emerge (Rotgans & Schmidt, 2017; Schiefele, 2009). In other words, situational and individual interest seem to be influenced by multiple mechanisms, and their relationship is not as clear-cut as it might seem from Figure 3.3; a more complex model of the relationships between different types of interest and between interest and intrinsic motivation was proposed by Schiefele (2009) and is captured in Figure 3.4.

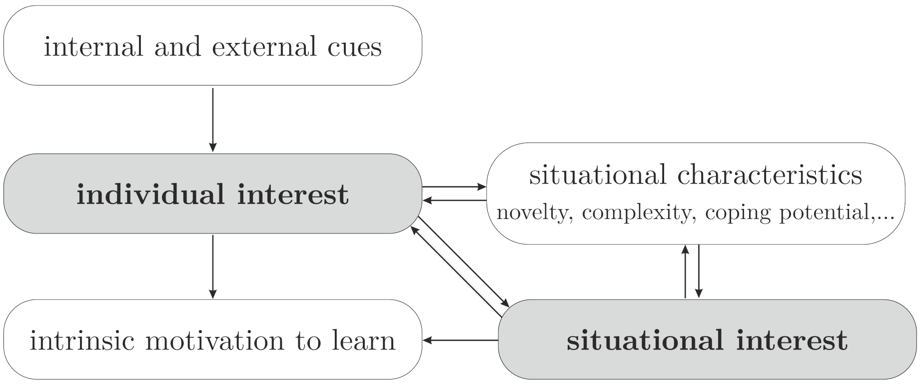

Figure 3.4. An alternative model of interest development; retrieved from Schiefele (2009).

3.3. Interest in the educational process

Although in the educational process we as educators naturally try to arouse students' interest in our disciplines, we primarily aim to develop their knowledge, skills, competencies, and attitudes. In other words, interest development is not our primary goal, but rather one of the means to achieve this primary goal. The question arises as to how effective this means is, i.e., to what degree stimulating interest contributes to learning gain. There have been many studies that address this question, and reviews of some of them are provided in articles such as those by O'Keefe et al. (2017), Rotgans and Schmidt (2017) or Schiefele (2009). The relationship between interest and learning gain is not straightforward, but the prevailing conclusions from these studies show that interest serves as a mediator of learning (Renninger & Hidi, 2011), it can increase learning gain and predict school performance (Harackiewicz et al., 2016; Köller et al., 2001) or it can be an important reason why students choose more challenging tasks (Inoue, 2007). Rotgans and Schmidt (2017) point out that there are also (albeit less numerous) studies that have not shown such effects; however, there does not appear to have been a reported negative impact of interest development on school achievement. At the same time, a positive effect on learning and knowledge gain is attributed not only to individual interest (where this is to be expected, as to a large extent, individual interest determines students' professional orientation and career choice), but also to situational interest (Rotgans & Schmidt, 2017). What appears to be of particular importance is the considerable influence of interest on success in academic contexts (Jansen et al., 2016), especially if the required activities are of low initial interest for many students (Harackiewicz et al., 2016).

In addition to the fact that interest influences knowledge, the inverse relationship is also true – the mere attainment of a certain level of knowledge influences the process of interest development. Rotgans and Schmidt (2017) point out that students' existing knowledge about the subject or growing knowledge contributes to their level of individual interest – as the authors state, *"the more people learn, the more extensive their interest becomes"* (p. 85).

In the models of interest development mentioned in the previous section, the crucial stage is the initial triggering of situational interest, which serves as a basis for the next stage. It is therefore relevant to ask what interventions and activities can be used in an ordinary class to trigger situational interest. In general, it is expected that these interventions should show novelty, surprise, challenge, or complexity (as summarized in Harackiewicz et al. (2016)), ideally in conjunction with coping potential (Schiefele, 2009). In the school context, the following activities seem to trigger situational interest: active learning methods (Blumenfeld et al., 2006), collaborative and team-based learning (Hidi & Renninger, 2006; Jeno et al., 2017; Schiefele, 2009), problem-based tasks (Harackiewicz et al., 2016), hands-on practical work (Abrahams, 2009; Erickson et al., 2020; Kácovský et al., 2023; Lin et al., 2013; Palmer, 2009), lecture demonstrations (Kácovský & Snětinová, 2021; Lin et al., 2013; Palmer, 2009; Walton, 2002) or projects and fieldwork (Harackiewicz et al., 2016; Hidi & Renninger, 2006; Schiefele, 2009).

At my workplace, many people have systematically, over decades, engaged in activities that fall into the above, i.e., those with the potential to arouse triggered situational interest – namely lecture demonstrations and hands-on practical work, both usually designed for the upper secondary level. As these activities are the focus of my research[2], I will introduce them in the following section.

[2] It would be unfair to my collaborators if I referred to this research only as „my research“, which is why I will use the term „our research“ in the following text.

3.4. Research context

As indicated at the end of the previous section, the subject of our research on intrinsic motivation are activities that have long been organized by the Department of Physics Education (Faculty of Mathematics and Physics, Charles University). It especially concerns two activities for upper secondary students, namely a performance consisting of physics lecture demonstrations (called DEMOs) and practical work in the Interactive Physics Laboratory. These activities exactly fulfil the features mentioned in the introduction of Chapter 3 – from the students' perspective, these are one-off events, with the Faculty organizers having minimal supportive meta-information about the participants. Further, I would like to take a closer look at these two activities.

Physics lecture demonstrations (DEMOs)

The DEMOs project involves regular performances consisting of physics lecture demonstrations and aimed at groups of upper secondary students. Usually from October to May (except during the covid-19 pandemic), the DEMOs take place one day a week; during that day, the same monothematic experimental session taking 75 minutes is typically repeated three times in a row. The topic of the sessions on a particular day is known in advance and teachers register for it online. The topics currently offered are *acoustics*, *electricity and magnetism*, *electromagnetic waves*, *ionizing radiation*, *mechanics*, *optics,* and *thermodynamics.* All the topics are offered with similar frequency throughout the year (five or six times) except for *electromagnetic waves* and *ionizing radiation*; these areas of physics are more rarely taught at upper secondary schools, and as such are only offered three times a year.

The experiments are performed by the employees of the Department of Physics Education. Typically, the presentation is lecture-centred, with only a few student volunteers participating in some experiments; otherwise, the students' role is rather passive. In some cases, students are encouraged to make predictions or hypotheses on how the experiment will continue or what the result will be; most often, however, they are asked for explanations only and as such, the whole ILD scheme (cf. page 4) is not applied. The experiments chosen for the monothematic session are predominantly based on the intended upper secondary physics curriculum, although there are certain experiments beyond it.

The event has a tradition of more than three decades and has an impact on many students and their teachers – every year, around 5,000 students visit the performances. Despite the considerable research potential, the DEMOs have not been the subject of any research until recently.

Interactive Physics Laboratory (IPL)

The idea to establish a laboratory intended for hands-on practical work at the Faculty of Mathematics and Physics in Prague was inspired by the House of Science in Stockholm, which – unlike the IPL – focuses not only on physics experiments but experimenting in science in general. With the support of the Faculty, the laboratory was put into operation at the end of

2008. The main goal of the IPL is to allow upper secondary students to grasp physics with their own hands, and to provide them with space, equipment, and guidance for small-group practical work on a particular physics topic.

At the beginning of each semester, the IPL team offers a list of days when experimental sessions will take place; it is typically one day per week, but there is no regular pattern. On the day, two IPL sessions starting at 8:30 a.m. and 11:00 a.m. take place, each with a duration of 120 minutes. Teachers book the date and time they prefer online; since one IPL session is limited to 16 students, a typical Czech class of about 30 students has to be split by the teacher in half; these two groups often visit two consecutive sessions in one day.

Simultaneously with the date and time, the teacher also chooses the topic of the experimental set that the IPL team should prepare for the students. There are currently ten topics offered, specifically *electrostatics*, *oscillations and rigid body mechanics*, *quantum effects in microworld*, *magnetic field of solenoids*, *optics (qualitative approach)*, *optics (quantitative approach)*, *rotating frames of reference*, *thermodynamics (qualitative approach)*, *thermodynamics (quantitative approach)* and *motions under gravity*. Every experimental set consists of four to six experimental stations, each of which is composed of a series of consecutive experiments. These experiments usually involve both quick low-cost experiments as well as measurements that could hardly be carried out in the classroom because of the required time or equipment.

Students enter the laboratory with their teacher and after being acquainted with the scheme of their visit, they are divided into small groups according to their (or rarely the teacher's) wish and start working on one of the experimental stations. The stations are designed to take ca. 30–40 minutes for an average students' group; after completing one station, the group moves to another one. The fastest groups can complete four stations during their visit, which could be the entire experimental set.

At every experimental station, students are provided with worksheets that guide them through the individual experiments. Since practical work in the IPL primarily has the form of structured inquiry (according to Banchi & Bell, 2008), worksheets usually contain (in addition to tasks to be solved) the elements of POE, i.e., space for estimations and predictions. During their work, students can consult their progress with two lecturers (pre-service teacher students and/or more junior employees of the Department of Physics Education) or even with their teacher. The role of lecturers is primarily supportive – students are led to maximum autonomy, and they remain responsible for the outcomes of their work.

At the end of the IPL session, every student group describes one of the experimental stations in a very brief oral presentation (2–3 minutes) that typically contains an introduction to the problem solved and a short description of the experimental procedure, major findings, and limitations. The presentation should be intelligible also to those groups which have not gone through the station being described. When leaving the laboratory, students take their worksheets home, giving their teacher an opportunity to build on the IPL session in his/her regular physics lessons.

Every school year, the laboratory welcomes ca. 70 school groups and more than about 1,000 upper secondary students.

Methodology

The methodology of our research is described in detail in the papers appended to this chapter in Section 3.6. However, to put things into perspective, let me provide at least a basic summary of methodological information The research questions are not presented here because they vary considerably depending on whether DEMOs or practical work in the IPL was explored; these questions are indeed formulated and discussed in the individual papers (Kácovský et al., 2023; Kácovský & Snětinová, 2021; Snětinová et al., 2018).

When exploring students' intrinsic motivation, we used a quantitative research design. For both the DEMOs and the IPL, we were interested in the instant feedback obtained immediately after the event.

As a research instrument, we used a paper-and-pencil questionnaire that consisted of three logical groups of items. The aim of the first group was to collect basic metadata about the respondents – students' gender, age, year of study, grade in physics and intention to study physics and STEM at university; in the case of the IPL, we were also interested in the number of members of the student's work group. The second group of items explored students' perception of physics as a school subject. On a five-point Likert scale, respondents were expected to rate six statements addressing (a) their attitudes towards physics (namely its popularity, difficulty, importance, and interestingness) and (b) their self-reported giftedness and diligence in physics (adopted from Pavelková et al. (2010)).

The third and crucial group of items examined students' perception of the one-off event they had visited (i.e., either the DEMOs performance or hands-on practical work session in the IPL). Each item had a form of a statement rated on a seven-point Likert scale. The scale score indicates the extent to which a statement is true, according to the students – a score of '1' means *very true*, a score of '4' *somewhat true* and a score of '7' *not at all true*. The items were adopted from the Intrinsic Motivation Inventory questionnaire (abbrev. IMI; Center of Self-Determination Theory, n.d.), a multidimensional tool that is grounded on the self-determination theory. Since not all seven IMI dimensions were relevant to our research context, we restricted our research instrument to items falling within five dimensions only. Their brief description provided by Monteiro et al. (2015) follows:

- *Interest/enjoyment* evaluates interest in and pleasure from an activity. This crucial dimension is considered the sole measure of intrinsic motivation.
- *Perceived competence* measures how effective individuals feel in performing a given task. It is considered a positive predictor of intrinsic motivation.
- *Pressure/tension* assesses whether participants experience pressure to succeed in a given activity. It is considered a negative predictor of intrinsic motivation.

- *Effort/importance* reflects how people invest their abilities in what they do. It could be considered both a predictor and a consequence of intrinsic motivation (Inzlicht et al., 2018).
- *Value/usefulness* that people internalize and develop more self-regulatory activities if they perceive the experience as valuable and useful to them. The dimension provides supplemental information when studying intrinsic motivation.

Data collection lasted one year for DEMOs and 3 years for the IPL; together, responses from more than 7,000 upper secondary students were collected – ca. 5,000 in DEMOS and ca. 2,000 in the IPL.

3.5. Current findings and future directions

To conclude this chapter, let me first briefly summarize our findings to date in the form of a qualitative summary, without statistical markers. Their position in the context of the existing literature is discussed in detail in the attached papers in Section 3.6 and as such, it is mentioned here only briefly. The results related to specific research questions are also not provided for here; these are only broken down according to our main areas of interest.

What does (not) support intrinsic motivation?

A crucial outcome of our research is the answer to the question of what role the individual dimensions of the Intrinsic Motivation Inventory (or the latent variables identified with them) play in relation to intrinsic motivation, more specifically to the inherent dimension of *interest/enjoyment*, and thus in the context of the above-described experimental activities.

The results show that what was most relevant to the expressed level of intrinsic motivation in both events was their subjectively perceived *value/usefulness*. This is in line e.g., with Gustafsson (2005) who reported large correlations between the dimensions of *value/usefulness* and *interest/enjoyment* in the case of cooperative work in physics education. Hence, convincing students of the meaningfulness and usefulness of a physics experimental activity is essential for stimulating their situational interest. This appeal should lead physics educators to design/innovate their experimental activities (lecture demonstrations, practical work) not just to “show the beauty of physics”, but to make them adequately relevant to students’ everyday life.

On the other hand, the dimensions of *felt pressure/tension* and *perceived competence* are rather weakly related to intrinsic motivation. Consistently with the theoretical framework, we confirmed that *felt pressure/tension* serves as a negative predictor of intrinsic motivation, but its effect is relatively small. In the case of lecture demonstrations, we cannot even (given the results of the factor analysis) talk about this dimension as such, but rather about isolated items related to felt pressure. The *perceived competence* dimension was included in the research instrument only in the case of practical work in the IPL and appeared not to be essential for intrinsic motivation, being its positive but relatively weak predictor.

The issue of effort/importance

After *value/usefulness*, the dimension of *effort/importance* turned out to be the second most important latent variable positively correlated with intrinsic motivation – a higher level of expressed effort was generally related to higher IM. Apart from that, the greater the perceived difficulty of physics as a school subject, the more positively the students assessed both events in terms of intrinsic motivation.

Such conclusions may appear surprising, as some models in cognitive psychology or economics assume that when people are given a choice, they tend to avoid effort (Inzlicht et al., 2018). However, this is only one perspective since effort might be conceptualized in two different ways. Inzlicht et al. (2018) discuss the so-called *effort paradox* emphasizing that effort could be demanding and rewarding at the same time. Assuming such a theoretical framework, our results show that in the case of both investigated events, the rewarding effect of effort presumably prevails. However, even though we know that the correlation between the *effort/importance* of any activity and intrinsic motivation is positive, it is not clear what is going on in the minds of the specific respondents. The reason is that the effort invested could be both the support for intrinsic motivation ("the activity is challenging for me, therefore I enjoy it") and its consequence ("I enjoy the activity, therefore I put more effort into it"). Our data do not enable us to distinguish which implication is the most common in the students' population.

When comparing the two events under investigation, students express higher invested effort in the practical work of the IPL, which is not surprising given that in the DEMOs performances, the role of students is largely passive. The fact that even in the IPL, the correlation between intrinsic motivation and the effort/importance dimension is positive suggests that the difficulty of the practical work tasks solved is adequate to the students' abilities. If the demands were too high (discouraging for the students) or too low (not challenging enough), we probably would not find such a positive relationship.

Gender differences

Based on the metadata about students, we confirmed that in terms of their attitudes, girls are more critical of physics as a school subject than boys, which is largely consistent with previous studies (e.g., Reid & Skryabina, 2003; Trumper, 2006; Weinburgh, 1995). Specifically, compared to boys, girls in our research reported lower perceived importance and general liking for school physics and its higher difficulty for themselves (Kácovský & Snětinová, 2021). However, when it comes to the perception of the two events under investigation, girls' and boys' assessment of them is practically the same. Thus, it seems that the gender gap that persists in the perception of physics as a school subject does not necessarily translate into the context of one-off events.

The only truly significant gender difference we identified is the lower perceived competence reported by girls during practical work. This finding is in line with previous studies (e.g., Kokott et al., 2018; Murphy, 1993; Murphy & Whitelegg, 2006) and our direct experience from the laboratory that girls are more likely to label themselves as "talentless at physics". This gender gap in competence is often attributed to general social influence, starting from early-childhood gender stereotypes ("boys play with machines, girls with dolls"), continuing with the perception of science as a masculine discipline (Farland-Smith et al., 2017) and ending e.g., with girls' general reluctance to work with electronic devices (Murphy, 1993).

Self-reported giftedness and diligence: Strongly polarizing variables

As already mentioned in methodology (in Section 3.4), in the second part of the administered questionnaire, the respondents assessed six statements about physics as a school subject. These statements were intended to help us get a more general idea of the longer-term attitudes of a particular student that frame their current perception of the DEMO or IPL. In the data analysis, two self-reflective statements in which students were asked to express how they perceive their giftedness and diligence in physics appeared to be very interesting.

In both DEMOS and practical work in the IPL, responses to these items correlated very strongly with intrinsic motivation, with higher self-reported giftedness and diligence significantly predicting higher scores on the *interest/enjoyment* dimension. Of the two self-reflective items, perceived diligence had the larger effect size. Indeed, this item polarizes the population of respondents considerably – to illustrate, in the case of DEMOs, the average score on the *interest/enjoyment* dimension was 1.88 for students who labelled themselves as very diligent and 4.15 for those who admitted laziness (both on a scale from 1 to 7).

Such results open up the question of to what extent the expressed giftedness and diligence are purely related to the personality and internal "setting" (such as self-confidence, shyness, modesty, etc.) of a particular student and to what extent these can be stimulated by external factors. The data suggest that if a teacher builds a more enduring sense in students that they are gifted in the subject and that they meaningfully invest their diligence in it, he or she is more likely to succeed in stimulating situational interest in these students.

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Future directions

The evaluation of the robust data collected during the research on intrinsic motivation continues to this day and still offers interesting publishing opportunities. Currently, the aims of the research are diverging into multiple future directions.

One of these directions includes – in addition to the two activities described in Section 3.4 – also a third experimental activity designed for upper secondary school students and organized by our Department. This activity is a science show called Physics Through All Senses (Kácovský & Koudelková, 2016; Machalická & Koudelková, 2019), which, like DEMOs, is based on lecture demonstrations, but requires more active audience participation and is held directly at interested schools. Between 2019–2020, we administered the same questionnaire at these shows like at the DEMOs performances, obtaining responses from approximately 3,000 respondents. Using the item response theory, the follow-up research aims to compare how scores on the different dimensions of the IMI questionnaire differ across the three events addressed (DEMOs, IPL, Physics Through All Senses) for equal groups of students.

The second direction currently being developed pertains solely to the data collected at DEMOs and aims to explore the link between how different physics performances differ in promoting intrinsic motivation and how the performer chooses experiments and interacts with the audience. This issue is the subject of the PhD study of Alexandr Nikitin who already addressed it in his Master's thesis at the Department of Physics Education. The performances of the individual performers were videotaped and are currently the subject of a quantitative-qualitative analysis based on a categorical system (Nikitin et al., 2022).

3.6. Original papers on the topic

1) Snětinová, M. et al. (2018). Hands-On Experiments in the Interactive Physics Laboratory: Students' Intrinsic Motivation and Understanding. *Center for Educational Policy Studies Journal*, *8*(1), 55–75.

2) Kácovský, P., & Snětinová, M. (2021). Physics demonstrations: who are the students appreciating them? *International Journal of Science Education*, *43*(4), 529–551.

3) Kácovský, P. et al. (2023). Predictors of students' intrinsic motivation during practical work in physics. *International Journal of Science Education*. Advance online publication. DOI: 10.1080/09500693.2023.2175626.

Paper:

Hands-On Experiments in the Interactive Physics Laboratory: Students' Intrinsic Motivation and Understanding

Authors: Marie Snětinová, Petr Kácovský, Jana Machalická

Published in the *Center for Educational Policy Studies Journal*, Volume 8, Issue 1, 2018, pp. 55–75.

DOI: 10.26529/cepsj.319

No Impact Factor

Paper:

Physics demonstrations: who are the students appreciating them?

Authors: Petr Kácovský, Marie Snětinová

Published in the *International Journal of Science Education*, Volume 43, Issue 4, 2021, pp. 529–551.

DOI: 10.1080/09500693.2020.1871526

Impact Factor (2021) = 2.518

Paper:

Predictors of students' intrinsic motivation during practical work in physics

Authors: Petr Kácovský, Marie Snětinová, Martin Chvál, Jitka Houfková, Zdeňka Koupilová

Published in the *International Journal of Science Education*, 2023. Advance online publication.

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Impact Factor (2021) = 2.518

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