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ORIGINAL RESEARCH

What matters for students' learning in the laboratory? Do not neglect the role of experimental equipment!

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Abstract

According to variation theory, it is essential to enable students to focus on the object of learning and discern its critical features, but the features that *it is possible* to discern often depend on the equipment used. Thus, in labs, the experimental technologies used may shape students' experience of focal phenomena, in a *human–mediating tools–world* manner, by placing some aspects of reality in the foreground, others in the background, and visualizing certain aspects that would otherwise be invisible. However, this mediating role is often neglected, and instruments and devices are often seen as having little cognitive value. Hence, the role of experimental technologies in labs as tools for learning is examined here through a case study, in which three sets of students investigated the same physical relationships (Newtonian motion in an inclined plane), but using different measurement technologies. The results demonstrate that what it is *possible* for students to experience in a laboratory is heavily influenced by the chosen technology. Some technologies do not afford the discernment of features regarded as crucial for students to learn. Furthermore, analysis of video recordings shows that the three sets of students' discourses differed, although they studied the "same physics". Hence, the role of experimental technologies in students' learning in labs should not be neglected, and their courses of action should be seen as material-discursive practice. Moreover, general conclusions about learning in labs should be drawn cautiously, specifying the conditions and technology used, and discussions about learning technologies should not be limited to the use of computers.

Keywords Learning in the laboratory · Technology in labs · Affordances · Variation theory · Mediating tools · Technology enhanced learning

Introduction

Almost 80 years ago, Müller (1940) argued that "there is little evidence to show that the mind of modern man is superior to that of the ancients. His *tools* are incomparably better" (my italics). He reminds us "that the history of physical science is largely the history

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of instruments and their intelligent use" (ibid.). Strikingly, for example, four centuries ago Galilei (1610/1989) revolutionized the practice of science by introducing a major perceptual technology[1]: the telescope. This amplified users' senses and "made hitherto invisible things visible" (van Helden 1989). Importantly, Galilei (1638/1954) not only *observed* nature using a technology but also subsequently described, in *Two New Sciences*, active experimentation using technologies both in experimental setups and for measuring physical quantities.

Many new technologies have emerged and been used in scientific inquiry and learning science since the days of Galileo and his introduction of technology into the practice of science. Moreover, in recent decades there has been increasing interest in "technology-enhanced learning": the use of new technologies to support the learning of science (e.g. Kyza et al. 2009). The learning technologies that it has been claimed can support meaningful learning in science have been categorized by Kyza et al. (2009) as: (a) *scientific visualization tools*, (b) *databases*, (c) *data collection and analysis tools*, (d) *computer-based simulations*, and (e) *modelling*. The use of laboratory learning activities in formal instruction in science and engineering is intimately related to technology-enhanced learning, as technologies for data collection and analysis (and other technologies) are typically used in labs (in various ways) to support student learning. Indeed, the laboratory is seen as having a "central and distinctive role" in science education (e.g. Hofstein and Lunetta 1982, 2004) and as a learning environment that "sets science apart from most … subjects" (White 1988).

Nevertheless, the emergence of affordable and more powerful personal computers has raised questions regarding the possibility of "virtual labs"—where technology is used in the form of computer-based simulations—successfully replacing "real labs"—where technology is used in the form of data collection and analysis tools. Investigations of this possibility and related issues have yielded conflicting indications. Some studies have found that simulations can provide better, or at least equal, learning outcomes (e.g. Zacharia and Olympiou 2011; Chini et al. 2012). However, others have found that simulations have detrimental results, or tend to create virtual worlds that hinder students' development of links between theories and models to objects and events in physical reality (e.g. Lindwall and Ivarsson 2010; Jensen 2014). Moreover, it is important to recognize that a scientific theory or model is "always merely an *approximation* to the complete truth" (Feynman et al. 1963, italics in original), as it is inevitably based on simplifications, assumptions, and limitations, which might not be valid in a practical situation. Furthermore, complex interactions may occur in real phenomena that limit the applicability of theories and models. Hence, there are clear theoretical limitations to the ability of simulations and virtual labs to replicate "reality", and as succinctly stated by Feynman et al. (1963), "the principle of science … is the following: *The test of all knowledge is experiment.* Experiment is the *sole judge* of scientific 'truth'."[2] (italics in original).

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[1] In this paper, the term "technology" is most often used to describe equipment, instruments and devices used for performing observations and making measurements in science and engineering. In addition to terms such as "instrument", ", equipment", ", apparatus" and "devices", the terms "artefact"/"artifact" and "agencies of observation" can be found in the literature.

[2] The quote from Feynman et al. (1963) should not, of course, be interpreted as a claim that establishing scientific "truth" from an experiment is simple and straightforward. There are numerous complications, as detailed in, for example, an insightful discussion regarding the philosophy of experimentation presented by Hacking (1983). However, the quote highlights the empirical essence of the natural sciences.

To return to the issue of students' learning in the laboratory: the description of the work by Galilei indicates that in the laboratory one does not have direct experience (*human–world*) of the world, but primarily a mediated experience (*human–tool–world*), shaped by the use of physical and symbolic tools (e.g. Dewey 1925/1981; Ihde 1991). The physical tools (the technologies used) function as "agencies of observation" (Bohr 1958), i.e. as tools for collecting, analysing and presenting physical data. In labs, as Dewey (1925/1981) notes, "appliances of a technology [such as] the lens, pendulum, magnetic needle, [and] level [are deliberately adopted in scientific inquiry] as *tools of knowing*". Although experience in labs is mediated using "appliances of technology", the role of these experimental technologies in students' learning in laboratories has, with few exceptions, rarely been studied or problematized in educational research. This may partly be due to learning activities in the laboratory being commonly seen as providing direct, practical and concrete experiences of the physical world (e.g., Hofstein and Lunetta 1982; Trumper 2003; Singer et al. 2006). Another reason may be the traditional belief "that … instruments and experimental devices … *per se* … have no cognitive value" (Lelas 1993), i.e. they are seen as merely neutral vehicles for the transportation of information. Hence, technology in the form of experimental equipment is commonly seen as something that is simply "manipulated" (e.g. Lunetta 1998; Lunetta et al. 2007). Accordingly, Hucke and Fischer (2002) explicitly describe "object-related" action (manipulating objects) as a low complexity level of cognition and "concept-related" action (manipulating ideas) as a high complexity level. That is, in traditional beliefs about science, the technological means by which nature is perceived leaves no trace in our conceptions of nature (e.g., Kroes 2003). Popper (1972), for example, restricted his epistemology to the "world of language, of conjectures, theories, and arguments". Furthermore, if "tools and artifacts" are discussed at all they are, as described by McDonald et al. (2005), "generally referred to, rather than described, or seriously studied" and technology is often taken to be synonymous with computers.

A consequence of these views is that the role of technologies is often neglected or taken for granted, and researchers focus instead on the concepts, ideas, and structures of labs, for example, how "open" labs are (e.g. Domin 1999). Researchers may also treat real physical labs as homogenous settings when comparing them with, for example, virtual labs. The views described above may also result in educators lacking awareness of the role of experimentation in a curriculum, and failing to exploit the full advantages of experimental technologies and labs for learning. Furthermore, neglecting the role of measurement technologies in science and engineering leads to naïve realism or naïve idealism (Ihde 1991; Ihde and Selinger 2003).

Thus, investigations of technology-enhanced learning in science and engineering should include detailed consideration of the role of the experimental technology used to promote students' learning in labs. As succinctly expressed by Marton et al. (2004): "If we are interested in how students learn … we must ask ourselves what critical features of the object of learning students can *possibly discern* in a particular classroom situation" (my italics). This paper examines the affordances of experimental technologies, and the restrictions they impose, as tools for learning. More specifically, it considers whether different technologies that can be used to study the same object(s) of learning have different cognitive values and afford different possibilities for learning. The analysis is based on observations drawn from a case study in which three sets of students investigated the motion of a body in an inclined plane, using different measurement technologies. Since all the students investigated the "same physics" (Newtonian motion), the learning possibilities afforded by the different technologies could be studied and compared.

Learning and awareness

A later section presents background information about the cases studied, but the general theoretical framework of the investigation is summarised here. Key elements of the framework are variation theory and theories of mediated experience and awareness, rooted in pragmatism and (post-)phenomenology. However, most of the results and conclusions are also consistent with, and could be described in terms of, the main tenets of other theories, such as "conceptual conflict" (e.g. Hewson and Hewson 1984) and "cognitive conflict" (e.g. Posner et al. 1982) theories.

An important concept in various educational philosophies and theoretical frameworks (such as pragmatism, phenomenography, phenomenology, and activity theory) is *intentionality*—the idea that learning, thinking and experience cannot be studied in isolation from their content. Meaning emerges as a person directs his or her awareness to an object; "There is no learning without something learned, there is no thinking without something thought, there is no experiencing without something experienced" (Bowden and Marton 1998). Awareness is the totality of our experiences, but it is differentiated in such a way that some aspects are brought to the fore, i.e. focal awareness, while other aspects are marginalised and constitute the background (Gurwitsch 1964). Hence, learning is seen as "a qualitative change in the *relation* between the learner and that which is learned" (Booth 2004, my italics).

Learning through variation

Dewey (1925/1981) regarded labs as important environments for learning, and experimentation as an "indispensable instrument of modern scientific knowing". He points out that we learn through experiencing differences, so by intentionally altering and controlling conditions in experiments "subject-matters which would not otherwise have *been noted*" may be disclosed and discovered (my italics).

This recognition is further elaborated in *variation theory*, developed by Marton and colleagues (e.g. Marton and Booth 1997; Bowden and Marton 1998; Marton and Tsui 2004; Pang and Marton 2005; Marton and Pang 2006, 2008; Marton 2015). This theory provides an explanatory framework for describing the conditions required for learning. It holds that for learning to be brought about, the critical aspects of the object of learning must be discerned and enter the learner's focal awareness. Central concepts in variation theory are *discernment*, *simultaneity* and *variation*. Learning is seen as the process of developing certain capabilities and values that enable the learner to handle novel situations effectively. Powerful ways of acting are seen to emerge from powerful ways of seeing. Thus, aspects that can be discerned by the observer determine *how* something is seen, or *why* it is seen in a particular way. People discern certain aspects of their environment by experiencing variation. When one aspect of a phenomenon or an event changes, while one or more aspects remain the same, the one that changes is the one that will be discerned. One of the main themes of variation theory is that the pattern of variation inherent in the learning situation, the *space of learning*, fundamentally influences any learning within it.

Experiencing variation amounts to experiencing different instances of the object of learning simultaneously. This simultaneity can be either *diachronic* (experiencing, *at the same time*, aspects of something that we have encountered at different points in time) or *synchronic* (experiencing different co-existing aspects of the same thing at the same time).

As mentioned earlier, Marton et al. (2004) related learning to what it is *possible* for students to experience in a particular classroom situation, stating that in a learning situation "the critical aspects that it is *possible* [for a student] to discern … make up the *enacted* object of learning" (Marton 2015, my italics). Another important distinction in a learning situation is the difference between the *intended* object of learning (the critical aspects of a given object of learning that a student should discern) and the *lived* object of learning (the critical aspects that *can be discerned* and that the student *actually discerns*, i.e. what the student learns in the end).

Variation theory has been used as a theoretical framework in several empirical studies of learning in science and engineering (e.g. Carlsson 2002; Linder et al. 2006; Runesson 2006; Carstensen and Bernhard 2009; Fraser and Linder 2009; Ingerman et al. 2009a, b; Bernhard 2010; Ling and Marton 2012). Reviewing these contributions is beyond the scope of this paper, but they all highlight the importance of variation for enabling students to discern the critical aspects of the object of learning. They also confirm another observation by Dewey (1925/1981), that experiments (and hence labs) are educational tools that an instructor or course designer can use to create variations in such a way that phenomena can be discerned.

Mediated experience in the laboratory

Since students' experiences in science and engineering laboratories are mediated, *human–technology–world*, through experimental technologies (which may dictate what enters their focal awareness and what remains in the background), there is an obvious need to consider how the world can be experienced through these technologies. As mentioned earlier, Dewey (1925/1981) saw technologies as "tools of knowing" in experiments. This is because mediation *amplifies* some aspects of the world, enabling the human investigator to perceive some things more clearly or to perceive things that are *imperceptible* without the mediating technology. An improved telescope, for example, enabled Galilei (1610/1989) to see stars of the 7th to 12th magnitudes, and to discover Jupiter's moons. Thus, a mediating technology will transform experience in some way. An equally important, but often neglected, aspect of this transformation of experience by a mediating technology is that it not only provides *amplification* but also inevitably causes some *reduction*. For example, a telescope dramatically reduces the visual field. Hence it took Galileo a week to determine the correct number of Jupiter's moons because some were outside the visual field of his telescope during some of his observations (Drake 1978). The telescope and the microscope are examples of the *magnification-reduction* structure that can be found in all technological mediations (e.g. Ihde 1979, 1990; Verbeek 2005; Kiran 2015).

When Galileo used his telescope, he saw a smaller portion of the sky in one glance than he saw using the "naked eye", but he could still perceive only wavelengths that are visible to the human eye. In modern astronomy the range of wavelengths that can be used to obtain information has been vastly extended. However, it is important to realise that although the use of new wavelengths enables the observer to see previously "invisible" features of studied objects, other features will either remain or become invisible, depending on the wavelength range of the instrument used (cf. Ihde 2007, 2010). Similarly, in materials science, there are differences in what can be "seen" using electron, X-ray, or neutron diffraction instruments (e.g. Bacon 1975; Bowen and Hall 1975), while in medicine different radiological methods allow different observations (cf. Berg

Friis 2015). These are examples of the *revealing-concealing* structure found in technological mediation (e.g. Ihde 1979, 1990; Kiran 2015).

Mediation through a technology has also an *enabling-constraining* structure, and an *involving-alienating* structure (e.g. Kiran 2015). In summary, the concept of mediation encapsulates an important but often overlooked aspect of measuring technologies used in techno-science—they are not neutral transmitters of information. Instead, as pointed out by Bohr (1958), it is impossible "in physical experience … to distinguish between phenomena themselves and their conscious perception" through measuring instruments. Moreover, he argues, "tools of observation play [a role] in defining … physical concepts".

All dimensions of mediation contribute to what enters our focal awareness and what is pushed into the background, i.e. mediating technologies strongly influence *figure-background* relationships in human experience. Based on the theories of mediated experience presented above, I propose a simplified model (Fig. 1) of the reductions of horizons involved in human inquiry when using experimental technologies. Amplifications & reductions, revelations & concealments, and enablements & constraints are involved in each step of the *subject matter—object of study—tools for measuring and collecting data—tools for processing and (re-)presenting data* chain. The first step, the selection of the *subject matter* for investigation, sets choices and restrictions regarding the concepts that matter (sic!), i.e. the concepts that will *and will not* be applicable or relevant. The cases discussed in this paper concern the domain of mechanics within the subject physics. Hence, within such an investigation, not only non-physical concepts but also physical concepts linked to domains outside mechanics (at least in our current understanding of the domain), such as colour, are beyond the sphere of the inquiry. As discussed in more detail below, further *amplification*, *revelation* and *enablement* are afforded—and *reduction*, *concealment* and *constriction* imposed—by the choices of set-ups used as an object of study and the technologies used as tools for measuring and collecting data. Finally, the tools used for processing and (re-)presenting the experimental data afford and impose further *amplification–reduction*, *revelation–concealment* and *enablement–constriction*, for example, through signal processing.

In addition, the limitations of human perception (indicated by the dashed ellipses in Fig. 1) must be considered. A student will not necessarily perceive what an experimental technology enables him or her to perceive. What is actually perceived (and hence provides material from which it is possible for him or her to learn) depends on the instructional features of the situation, such as scaffolding from the teacher and

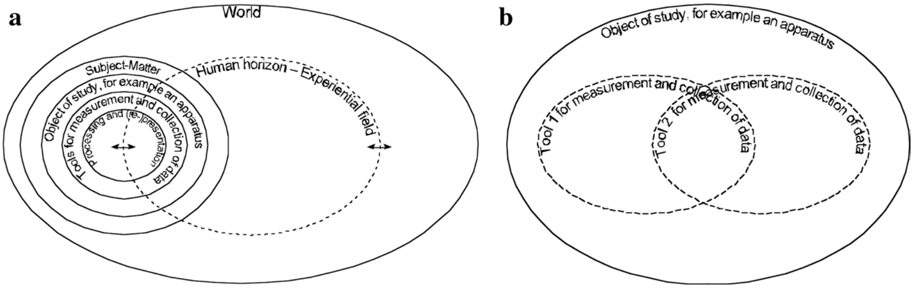

Fig. 1 Illustration of the selective horizons of experimental technologies and humans in relation to humans' life-world: **a**. A general model of succesive selective horizons. **b**. Illustration that different tools for measurement and collection of data can have different horizons

instructions. Hence, as indicated by the arrows on the dashed ellipse, human foci can be shifted through educational interventions. Indeed, human agency is involved in all steps in the chain, and that the categorizations in the model shown in Fig. 1 are solely for analytical purposes. In a real case, there are no sharp "boundaries" between them. Accordingly, Harré (2003) highlights this by describing it as "apparatus – world complexes".

Furthermore, as indicated by the dashed ellipses in Fig. 1a, students experience physical phenomena not only through experimental technologies. Other tools such as mathematics, drawings and verbal language are used, and senses such as touching, hearing, smelling, and tasting may be involved, in addition to seeing. Indeed, there are strong indications in the literature that learning is enhanced by the use of multiple modalities (e.g. Kozma 2003; Ainsworth 2008; Jornet and Roth 2015). However, in this paper the specific analytical focus is on the role of experimental technologies.

Aims, setting and methodology

As already mentioned, Marton et al. (2004) related learning to what it is *possible* for students to experience in a particular classroom situation, but the possible experiences that are enabled by mediating technologies in labs, and the constraints imposed by these technologies, are generally neglected or trivialised. The aim of this paper is to elucidate "the way in which something *can be* experienced" (Marton et al. 2004, italics in original) when mediated by technologies (agencies of observation) in science and engineering education laboratories. The main research question (RQ1) addressed is: "Do experimental technologies in the form of different instrumentations differ in the *possible* learning they enable when the same object of learning is studied". To rephrase this in terms of the terminology used in variation theory: "Do different technologies lead to different possible *enacted* objects of learning?". A secondary research question (RQ2) is: "Are the observed differences in students' courses of action associated with the instrumentation used?". Again, in variation theory terminology, this becomes: "Are there differences in students' *lived* objects of learning?".

We have addressed these research questions in a case study, focusing on the learning affordances (and constraints) of three experimental setups in labs for studying the motion of a body (cart or glider) under uniform (gravitational) acceleration in an inclined plane. In these labs, students studied the same physical relationships, but used three different measurement technologies: *photogates*, a *tape timer*, and *probeware (MBL).*[3] These measurement technologies are commonly used in schools and the "same physics" was studied. Thus the instrumentation varied but not the intended object of learning. Hence, the use of three technologies should enable differences (if any) in enacted and lived objects of learning afforded by the technologies to be detected (cf. Gibson 1979). Further, we expected that the results could be understood and generalized outside the domain of physics.

This was not an intervention study, and the labs discussed in this paper were regular labs in physics courses and they were studied in naturalistic settings, i.e. ordinary scheduled labs. In all cases, the labs were instructed by well-qualified teachers with good reputation; none of the teachers had less than 20 years of teaching experience. The *photogates* and *tape timer*

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[3] This type of system is often called "microcomputer-based laboratory" (MBL). However, the abbreviation "MBL" is commonly associated with an "interactive engagement" pedagogical approach and I have chosen to use the term "probeware" to stress that I am analysing the affordances of a technology.

labs were parts of a physics course in a foundation year programme for students who had not specialised in science (or engineering) in upper secondary school. Thus, the level of the course corresponded to a similar course in the Swedish upper secondary school, although the students were slightly older. The *probeware* lab was part of a science course in a teacher education programme. As in the foundation year programme, the students participating in this programme were not required to have studied physics in upper secondary school. Hence, all the students were at approximately the same scholarly level with regard to the physics content. In all three cases, the tasks in the labs were typically performed by groups of 2–3 students.

To address RQ1, the aspects of accelerated motion in an inclined plane that *could* be experienced through the measurement technologies and experimental equipment provided in the labs, and the dimensions of variations they afforded, were identified and circumscribed by phenomenological inquiry (Ihde 1986). This method can be seen as a "blend of empirical and philosophical research methods" (Rosenberger and Verbeek 2015; see also Verbeek 2015). The results of this inquiry, presented below, analyse the *enacted object of learning*, i.e. "the researcher's description of whether, to what extent and in what forms, the necessary conditions of a particular object of learning appear[ed] in a certain setting" (Marton et al. 2004), by means of the *experimental technologies* and *agencies of observation* used in the labs.

To address RQ2, the course of action of each group of students in the labs was recorded by a (separate) video camera. Three, two and eight groups were recorded in the *photogates*, *tape timer* and *probeware* labs, respectively, resulting in about 15 h of video. This was subsequently used to detect typical patterns of interaction and to find evidence supporting, or refuting, hypotheses regarding the generality of these patterns (Jordan and Henderson 1995). I particularly focused on how the students interacted with and through the technology, what they did, what they made relevant, and how they oriented themselves towards the object of learning (cf. Verbeek 2015). All the video recordings were repeatedly viewed in this initial analysis, then episodes containing particularly interesting and comparable activities related to the research questions were identified and transcribed to allow detailed examination of patterns of interaction. In the transcriptions, standard conventions used in conversation analysis were used (ten Have 2007) and the transcripts presented here have been translated from Swedish into English. Finally, the patterns of interaction observed in the labs involving the use of the three different technologies were compared and contrasted to find similarities and "differences that make a difference" (Bateson 1972; cf. Lindwall and Ivarsson 2010). This analysis examined "the lived object of learning, i.e. the way that students [saw, understood, and made sense of] the object of learning" (Marton et al. 2004). This paper focuses mainly on the affordances and constraints of the *experimental technologies* used in the labs for the possibilities of discernment and learning (RQ1). Findings concerning the students' lived object of learning (RQ2) are here only briefly described in the Results section. Some illustrative excerpts from transcripts regarding these findings are presented. Although important, the roles of *instructions* and the *instructor* in relation to the enacted and lived objects of learning were ignored in this study, and the sole analytic focus was on the role of the three technologies.

Motion in an inclined plane

The primary issues investigated were the learning affordances and constraints of the technologies used in the three experimental setups. I present here some background information related to motion in an inclined plane to complement the general background presented earlier. In addition to his optical studies (also mentioned above), Galilei was one of the first scholars to observe motion in an inclined plane and systematically investigate what we currently call "uniformly accelerated motion" (e.g. Galilei 1638/1954; Drake 1978; Garfinkel 2002; Ford 2003). Studying motion in an inclined plane has several advantages over studying the motion of a freely falling body, because the acceleration is lower ($a = g \cdot \sin\theta$, where θ is the angle of inclination of the plane, g is the acceleration due to gravity and a is the acceleration under which the body moves), so the motion is slower and easier to observe. Given the difficulties of measuring time accurately during Galilei's period of history, this was essential. He studied the motion of objects on various slopes and argued that free-fall was a limiting case, where $\theta = 90°$.

The students in all three labs considered here faced the problem of making the same conceptual distinctions as Galilei, although they used more advanced measurement technologies. One of Galilei's major accomplishments was to differentiate clearly (in modern terms) between "average speed", "instantaneous speed" and "increments of speed". However, Galileo failed to make sense of accelerated motion for many years, since his initial hypothesis was that "increments of speed" are related to distance travelled rather than time, i.e., he initially believed that $a = \Delta v/\Delta x$, where v is velocity (using our current notation) and x is position. However, he eventually concluded that (in modern notation) $a = \Delta v/\Delta t$, where t is time, reflecting the fact that acceleration is constant for a body either in an inclined plane or in free fall (Galilei 1638/1954; Drake 1978; Ford 2003).

It is illuminating to consider the patterns of variation that may be discernible in different motions in an inclined plane, as illustrated in Table 1 and Fig. 2, and consider these in the light of variation theory. If only accelerated motion downwards on an incline is studied (or if this is the only motion that can be studied), position, velocity and acceleration all have the same direction and hence the same sign. Clearly, this limits the possibilities to discern and discriminate between these concepts, required by variation theory.

Laws (1997) contends that a good understanding of kinematics (laws of motion) is essential for the understanding of dynamics (laws of force and motion). However, various researchers (e.g. Trowbridge and McDermott 1980, 1981; Bowden et al. 1992; McDermott 1997) have shown that many students have problems understanding basic concepts of kinematics. Many students have difficulty distinguishing between velocity and change of velocity. They commonly believe that acceleration is always in the direction of motion, and

Table 1 Patterns of variation of position, velocity and acceleration in the motion of a body in an inclined plane (and thus under constant acceleration)

Concept	Graphic form	Kinematic expression	Motion in an inclined plane		
			Sign and change tendency		
			Up	Turn	Down
Position $x(t)$	Quadratic	$x(t) = x_0 + v_0 t + 1/2 \cdot at^2$	+ (decreasing)	+ (momentarily constant)	+ (increasing)
Velocity $v(t) = \Delta x(t)/\Delta t$	Linear	$v(t) = v_0 + at$	−	0	+
Acceleration $a(t) = \Delta v(t)/\Delta t$	Constant	$a = g \cdot \sin\theta$	+ (constant)	+ (constant)	+ (constant)

The positive direction is arbitrarily chosen to be down the incline, away from the motion sensor or tape timer

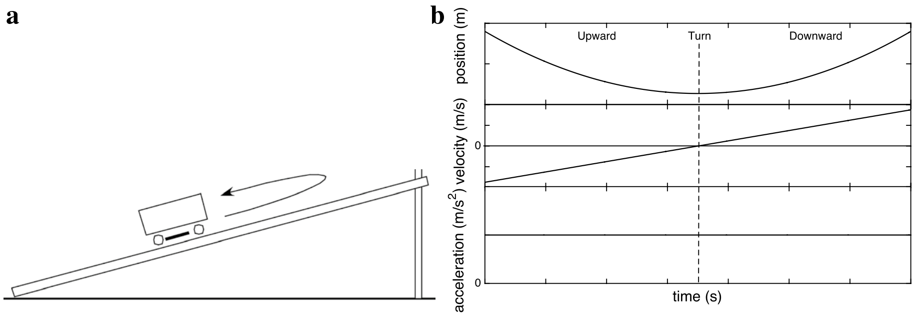

Fig. 2 **a** Motion of a cart in an inclined plane. **b** Theoretical graphs of position, velocity and acceleration against time for motion in an inclined plane. The positive direction is down the incline

that zero velocity implies that the acceleration must be zero. As will be shown in the next section, the different measurement technologies used in the labs have different affordances for addressing these difficulties in learning kinematics.

Results

Here, I first present the results of a comparative analysis of the affordances for learning related to the experimental technologies used to study motion in an inclined plane, in two parts. The units of analysis in the first part are the technologies and their properties relevant to RQ1: "Do experimental technologies in the form of different instrumentations differ in the *possible* learning they enable when the same object of learning is studied". The second part briefly presents results of an analysis of students' activities in the labs. Thus, the unit of analysis is students' interactions with the technologies used, and the findings are pertinent to RQ2: "Are the observed differences in students' courses of action associated with the instrumentation used?".

Analysis of affordances of the three experimental technologies (RQ1)

This part analyses the affordances of each of the three technologies used, then compares and contrasts these affordances.

Photogates

Figure 3 shows the experimental setup with a glider on an air track. The track is inclined and the air track system provides low friction between the track and the moving object to be observed (glider). A 'flag' is attached to the glider, which blocks the light beam from the two photogates, designated A and B, whenever the glider passes them. If Δs is the width of the flag and t_A and t_B are the times during which the light beams from gates A and B are blocked, respectively, the instantaneous speeds[4] can be calculated as $|v_A| = \Delta s/t_A$ and

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[4] Actually average speed throughout the few milliseconds during which the light beam is blocked, but for practical purposes it can be seen as instantaneous speed.

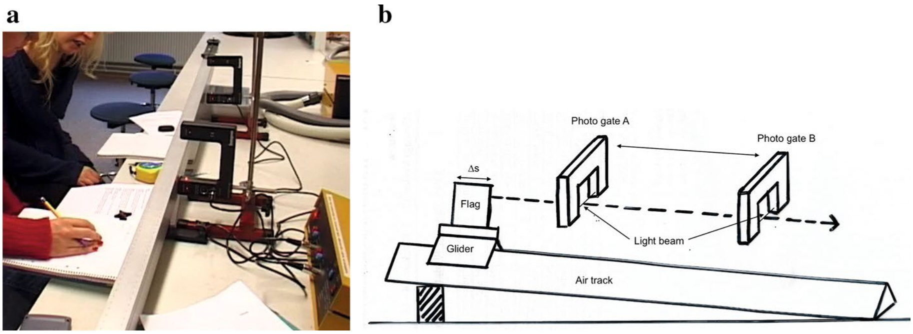

Fig. 3 Glider on an inclined air track. The glider's speed is measured using two photogates. **a** A photograph of the lab, and **b** a schematic diagram of the setup

$|v_B| = \Delta s/t_B$. In addition to measuring t_A and t_B, the instruments used in this lab can measure the time that the glider takes to move between gates A and B, t_{AB}.

The velocity and the acceleration as the glider slides down the incline, or up the incline (after an initial push), can be studied, and this enables the fallacy that acceleration must act in the direction of motion to be addressed. (In the lab session studied here, however, the students were not asked to observe uphill motion.) However, since only speed—and not the sign of the velocity—is directly determined using the experimental equipment, there is a risk that students make a sign mistake when asked to perform this task. In addition, the equipment cannot provide data showing that a glider given an initial upward push will have zero velocity, but non-zero acceleration, at its turning point. Furthermore, the electronic circuits used in this lab did not permit a complete cycle of motion (upwards then downwards) by the glider to be recorded in a continuous sequence, because a maximum of four time measurements can be stored. It would be possible to measure *only* the speed when the glider passes gates A and B in both directions and find that $|v_{A1}| \approx |v_{A2}|$ and $|v_{B1}| \approx |v_{B2}|$, where v_{A1} and v_{B1} are the velocities of motion upwards, and v_{A2} and v_{B2} are the velocities of motion downwards. However, due to the limitations of the electronics, neither t_{A1B1} nor t_{A2B2} could, in this case, be measured in the same measurement sequence, and it was not possible to determine a_1 (up) and a_2 (down) in a *single* experiment. It should be noted that it is not difficult to determine "acceleration" over distance, $\Delta v/\Delta x$. Thus, the "wrong" definition of acceleration is afforded, but not the "right" one!

Theoretically, more data could be obtained from plotting position-time, velocity-time and acceleration-time graphs by keeping one photo-gate at the same position and moving the other. However, this is a difficult and awkward procedure.

Tape timer

A *tape timer* makes dots on a paper tape at equal time intervals (in this case set by the frequency of the local mains electricity supply, 0.01 s, from 2 to 50 Hz). In this setup, the paper tape is attached to a cart that moves down an inclined plane, pulling the tape through the tape timer. By measuring positions of the dots on the tape, it is easy to obtain the data required to plot a position-time graph. Velocity-time and acceleration-time graphs can then be generated by numerical derivation ($v = \Delta x/\Delta t$ and $a = \Delta v/\Delta t$) (Fig. 4).

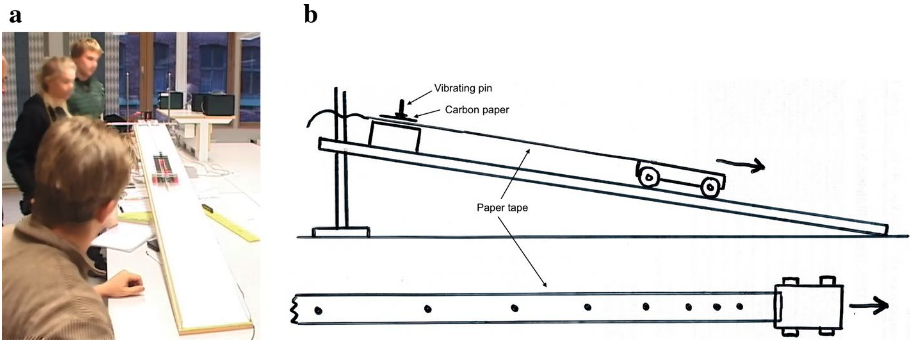

Fig. 4 Motion of a cart down an inclined plane, recording position as a function of time using a tape timer. **a** A photograph of the lab, and **b** a schematic diagram of the setup

Since the tape is pulled by the cart through the tape timer, only downward motion can be studied. Upward motion would buckle the tape. Thus, it is not possible to address the direction of acceleration by using this technology to record the cart's motion after pushing it up the inclined plane, or the magnitude of the acceleration at the turning point.

Probeware (MBL)

The third case also involves observation of an object moving up, down, or both up and down, an inclined plane. However, its position is measured (in real time) by a motion sensor attached via an interface to a computer, which can display (on a screen in real time) the cart's position, velocity, and acceleration as functions of time. Velocity and acceleration are obtained by numerical derivation by the computer.

In contrast to the previous cases, the graphs (Fig. 5b) are presented simultaneously with the actual motion. However, the most important feature in the context of this paper is that a

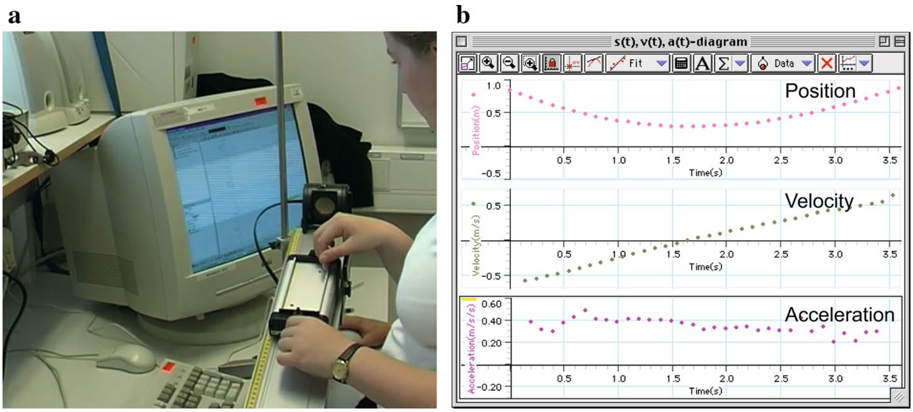

Fig. 5 Measurement of a cart's motion in an inclined plane measured by means of a motion sensor connected to a computer via an interface. The positive direction is down the incline, away from the motion sensor

wider range of phenomena can be studied experimentally. In this case, it is as convenient to study motion up the incline as motion down the incline. Furthermore, unlike the measurement technologies used in the other cases, the probeware technology allows measurement of the acceleration at the cart's highest point following an initial push upwards, thereby permitting the fallacy that acceleration is zero at this point to be addressed.

Comparing affordances

A summary of the affordances of the technologies for studying motion in an inclined plane (Table 2) clearly shows that what is *possible* to discern depends on the technology used.

Table 2 summarises the affordances of the measurement technologies used for studying motion in an inclined plane applied in the three cases, and confirms that what is possible to perceive or discern depends on the technology used. All three measurement technologies afford the determination of velocity, but its sign cannot be determined with the photogates setup and must be inferred by the experimenter, while the tape-timer setup allows observation of motion only in one direction. Changes of velocity (one of Galilei's important discernments) can be studied using all three setups. However, there are some subtle differences. The photogates' affordance for determining acceleration ($\Delta v/\Delta t$) is problematic because students first perceive and manipulate the distance between the photogates. In contrast, with the probeware technology, the acceleration is predefined by the measurement system. Studying $\Delta v/\Delta x$ is possible, but the settings in the software for doing this are not as straightforward as those used to obtain $a = \Delta v/\Delta t$. We see here that some conceptual distinctions have already been made for the user, or in the words of Wartofsky (1979) "artifacts (tools and languages) [are] objectifications of human needs and intentions … *already* invested with cognitive and affective content". Consequently, most users will never reflect on this (and other) pre-defined choices made in the measurement system.

The analysis of affordances presented above and summarised in Table 2 describes what is *possible* to observe with each technology. An integrated part of most measurement technologies is a system for recording data, then presenting or transmitting the recorded data. Table 3 summarises and presents the primary outputs of data obtained using each of the technologies, together with a summary of the mode of measurement and a description of how graphs displaying the acquired data are (or can be) generated. It seems reasonable to assume that what students actually perceive in a learning situation depends, to some extent, on how the experimental data are represented by the technology used. The primary output in a photo-gate experiment is a set of three numbers corresponding to the times t_A, t_B and t_{AB}. Measurements are only acquired when the flag of the glider blocks the light beam of

Table 2 Summary of affordances provided by the measurement technologies used in the considered cases

Measurement technology	Motion in an inclined plane			Velocity		Change of velocity	
	Up	Turn	Down	$\|v\|$	sign	$\Delta v/\Delta t$	$\Delta v/\Delta x$
Photogates	✓		✓	✓		(✓)	✓
Tape timer			✓	✓	(✓)	✓	✓
Probeware	✓	✓	✓	✓	✓	✓	(✓)

A tick, ✓, indicates an affordance, and a tick in parentheses, (✓), an affordance with some restrictions or difficulties, as explained in the text

Table 3 Summary of primary measurement output, types of measurement and type of graphing provided by the measurement technologies

Measurement technology	Primary output of experimental data	Measurement type	Graphing
Photogates	Numbers: (1) indicating the times, t_A and t_B, at which the light-beams in the photogates are blocked (2) indicating the time lapse, t_{AB}, between blockage of the first and second photogates	Point	Difficult
Tape timer	Dots on a paper tape (printed with a fixed frequency)—corresponding to positions of the tape at certain times	“Continuous”, manual	Manual
Probeware	Graphs showing distance, velocity and acceleration as functions of time. (Other outputs can be obtained by changing software settings.)	“Continuous”, “automatic”	Real-time, i.e. simultaneously with the experiment

Table 4 Summary of affordances of the equipment used in the three labs

Experimental equipment (object of study)	Slope of inclined plane	Mass of cart or glider	Friction
Glider on air track	✓	✓	
Cart used in tape timer lab	✓	✓	
Cart used in probeware lab	✓	✓	✓

As before a tick, ✓, denotes an affordance

one of the photogates, so they are taken at specific points in time. Graphing is not facilitated by this technology. In a tape-timer experiment, the primary outputs are dots printed on the paper tape as it is pulled through the tape-timer mechanism. The students must measure the positions of the dots on the tape and produce graphs manually. The measurement is practically (although not strictly) continuous. Finally, in a probeware experiment the primary outputs depend on the settings of the software controlling the data acquisition system. In a motion-in-an-inclined-plane lab, graphs of position, velocity and acceleration as functions of time are selected. As in a tape-timer experiment, the measurement can be regarded as practically continuous,[5] but the experimental data are collected automatically by the measurement technology and the resulting graphs are presented by the software in real time. Nevertheless, students must discern relevant parts of the graphs. Although the probeware experiment is typically set to present graphs (in this case), other outputs, such as tables of numerical values of position as a function of time, can be selected.

Other affordances than those summarised in Table 2 are available from the different experimental setups. For example, probeware allows measurements to be quickly repeated and experimental conditions to be varied quite easily. Like many other experimental technologies, it also allows observation of phenomena that cannot be directly observed by the naked eye through use of its software for processing and representing experimental data. It is also important to realise that the comparisons in Tables 2 and 3 are incomplete; there are other measurement technologies than those presented in the tables. Before the availability of inexpensive computers and sensors a tape timer afforded a possibility to graph motion in an inclined plane and photogates affords measurements of speed (and frequency) with higher accuracy than possible with a stop-watch. Hence, by tradition, these measurement technologies can be found in many school labs.

Moreover, there are differences in affordance of not only the measurement technologies (the agencies of observation), but also the experimental equipment (in a narrow sense). These are independent of the affordances of the measurement technologies described above, and are summarised in Table 4. The experimental equipment used in all three cases affords the slope of the inclined plane and the mass of the cart or glider to be changed. However, only the equipment used in the probeware lab allows the friction that affects the movement of the observed body to be changed (from a low-friction default). It should be stressed that this cart is not exclusive to the probeware measurement technology, and can be used with the other measurement technologies described in this paper. Moreover, the cart used in the tape timer lab or the glider on an air track can be used with probeware as

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[5] In reality, the data are discrete data points acquired with a certain sampling frequency. This discrete sampling has important consequences in some cases, for example in signal processing and control theory, but can be neglected here.

the technology for measurement. Furthermore, it can be noted that the (almost) frictionless air track is an adaptation of experimental equipment to idealized physical theories, i.e. changing the world to fit theories and models!

Students' courses of action in the labs (RQ2)

My main analytic focus in this study is on what the technologies used allow students to discern, and the discernments they do not readily permit. Therefore, only short excerpts of transcripts from records of (pseudonymised) students' courses of action in these labs are presented here. Students' courses of action in labs are framed by encounters with the instructions, the technology, the teacher, and other students (Bernhard 2010). Thus, factors other than the technology, such as courses of action, verbal and non-verbal communication, have influenced the discourses observed in the labs (as will be discussed in more detail in a forthcoming paper). With this caveat in mind, I briefly describe here my analysis of students' courses of action in the labs, with a particular focus on the role of the technologies.

An analysis of the complete video recordings of students participating in the photo-gate and tape-timer labs clearly shows that the students did not focus on the intended object of learning, uniformly accelerated motion. In the photo-gate lab, the discourse of all groups consistently centred on reading and noting the numbers (the times t_A, t_B and t_{AB}) from the electronics box, as illustrated in Excerpt 1. Concepts such as velocity, change of velocity and acceleration were barely mentioned.

Excerpt 1: Reading the display of the electronics box in the photo-gate lab

Standard conventions from conversation analysis (ten Have 2007) are used in transcripts.

1. Birgit: It only seems to read once
2. Ann: °Yeah°
3. Birgit: Then it stops
4. Birgit: Okay (.) the first result is here
5. (1 s)
6. Birgit: Eh, fifty-three point eight fifty three
7. Birgit: Fifty-four (.) let's see
8. Ann: [°Yeah°
9. Birgit: [Point nine
10. Ann: When we do
11. (2 s)
12. Ann: Second
13. Birgit: =Second
14. (3 s)
15. Birgit: Eh, thirty-two point three
16. (5 s)
17. Ann: Four well
18. (2 s)
19. Birgit: Mmm

In contrast, students performing the tape timer lab consistently focused on making sense of the dots on the tape, as shown in Excerpt 2. Although they had been instructed by the teacher to translate these dots into a position-time table to enable graphing, both of the groups studied only used the tape as an indicator of the time the cart took to move *one* fixed distance. Thus, they only determined the average velocity and not the instantaneous velocity. Also in this case, motion concepts featured very rarely in the students' discourse.

Excerpt 2: Students trying to interpret the dots on the tape in the tape timer lab

1. Bertil: We must measure equal length also
2. Adam: Yes we must do that (.) but
3. Bertil: Should we go for sixty-eight centimetres then?
4. ((Some dialogue excluded))
5. Adam: How many dots did you get?
6. Ceasar: A hundred and three
7. Bertil: A hundred and three
8. Ceasar: Mmm
9. Adam: Should we say how many seconds there are or how many hundredths there are? (.) Should we go for seventy or
10. Bertil: But what (.) we can do that (.) but we must have equal distance
11. Adam: Mmm, we take equal
12. Ceasar: We take the same position
13. Adam: Seventy seconds there (.) it is seventy there (.) we take distance instead (.) and measure it
14. Bertil: Yes, it is better to take a fixed distance instead (.) and see how many dots it is
15. Adam: Yes, that is suitable (.) for it is (.) or
16. Bertil: Mmm
17. Adam: It is shortest
18. Bertil: Probably it is

It is clear that the student did not perceive the "world" through a *human–technology–world* mediated experience, but numbers and dots produced by the measurement technology. This is a human–technology (–world) experience (cf. Ihde 1979, 1991). The students lacked the conceptual resources required to interpret the numbers and dots, and their discourse in these cases resembles the "conceptually blindfolded" discourse described by Bergqvist and Säljö (1994). The students struggled to make sense of the measurements and to produce graphs.

In contrast, in the probeware lab students' discourses consistently centred on making sense of motion concepts such as position, velocity and acceleration.

Excerpt 3: Students discuss velocity and acceleration at the turning point in the probeware lab.

1. Katrina: when it ((the cart)) reaches the highest point it ((the velocity)) is zero (.) and should roll down
2. Stina: m::
3. Katrina: velocity is equal to zero
4. (1 s)
5. Katrina: how large is the acceleration in this moment (.) it is zero
6. (3 s)
7. Katrina: no it is not ah::
8. (3 s)
9. Katrina: check that
10. Stina: [m::
11. Katrina: [when it is ze::ro
12. (3 s)
13. Katrina: at that time
14. (1 s)
15. Katrina: so it is on (.) it is constant
16. Stina: [m::
17. Katrina: [at two (.) at two seconds so is it zero (.) that is the velocity is zero (.) at that same time the acceleration is constant (.) that I think is very strange

Experimental results were presented in graphical form in real time, readily enabling simultaneous discernment. While in the tape timer and photo-gate labs students were supposed to produce position-time, velocity-time and acceleration-time graphs themselves, these graphs were produced by the computer–interface–motion sensor complex in the probeware lab. Nevertheless, in the probeware lab, students did not simply "copy and paste" the graphs into their reports without thinking. Instead, in contrast to the tape timer and photo-gate labs there students struggled to make sense of the measurements and to produce graphs, they struggled to make sense of the graphs and the physics involved. Indeed, connecting graphs and other representations to the science involved is not a simple task but is found to be a difficult task for most students (e.g. McDermott et al. 1987; Beichner 1994; Airey and Linder 2009; Planinic et al. 2013; Hill and Sharma 2015) and even for professionals outside their own domain of expertise (e.g. Roth and Bowen 2001).

It is instructive to examine not only the affordances provided by the measurement technologies used, but also the discernible patterns of variation afforded by the ability to observe motion up, down and at turning points, as is also indicated in Table 2. If accelerated motion only down an incline is studied (or it is the only motion that can be studied), position, velocity and acceleration will all have the same direction and hence the same sign. Clearly, according to variation theory this will restrict the possibilities to discern and distinguish these concepts.

In all three labs, conceptual distinctions and discernment of critical aspects were essential for the successful completion of tasks. However, in the tape timer and photo-gate labs, students *required* this ability *in advance*, i.e. they needed to know in advance what they were supposed to learn in the lab. In contrast, in the probeware lab, the students were not required to have this ability but were *led* to make conceptual distinctions and discern critical aspects by the affordances of the technology *and* a task-structure that had been developed based on variation theory. The lab *resulted* in a more powerful conceptual understanding (Bernhard 2010), which enabled students to successfully complete tasks. Thus, although the students were intended to "study the same physics", the physics they *performed*, as constituted in their courses of action, and the mediated relations formed, strongly differed.

Discussion

Validity and limitations of the results

The analysis of the cases presented here clearly confirms that the "critical features of the object of learning students can *possibly discern*" (Marton et al. 2004, my italics) depend on the experimental technology used, which thus answers the first research question. What it is *possible* for students to experience in a science or engineering laboratory is heavily influenced by the affordances of the chosen instrumentation. The analyses presented here of students' courses of action when studying motions of an object in an inclined plane show that affordances for discernment, variation and (hence) learning depend on the technology used. The experimental technologies analysed in this study do not include all commercially available technologies, and others may not be subject to the identified limitations. For example, systems that allow up to four photogates to be used simultaneously are available. Moreover, the technologies analysed in the three cases only afford the study of one-dimensional motion: other measurement technologies afford the study of three-dimensional motion (Ronen 1995). However, this does not contradict my conclusion that experience in labs is mediated through technologies, and hence the *possibilities* for discernment and variation depend on the technology used. Indeed, the existence of other technologies supports my claim that affordances for learning are technology-dependent. As the unit of analysis in the investigation related to RQ1 is the affordances of the technologies used, the results of the analysis will hold regardless of contextual features such as, for example, instructions and educational setting.

The analysis and conclusions presented in this paper are based on three cases of students studying accelerated motion of a body in an inclined plane. The paper gives examples of the variations in possibilities for learning afforded by the technology used. Many other examples of experimental technologies used in science or engineering settings that provide different affordances could have been chosen, and I maintain that in many other (if not *all*) cases, what is possible to discern depends on the technology used. For example, Haglund et al. (2015) have demonstrated how new cheap infrared cameras make it possible to carry out experiments in thermodynamics that gave immediate results, and Bernhard (1999) has demonstrated how probeware technologies enable the visualisation of oscillation modes in coupled harmonic oscillators. In both of these examples, the technologies make it possible to visualize in experiments phenomena and concepts that are impossible or difficult to discern with a "naked eye" (although some heat phenomena in thermodynamics experiments can, of course, be discerned somewhat rudimentarily with a "naked hand").

The use of probeware in mechanics labs and in interactive lecture demonstrations promotes good learning results, as measured by conceptual tests (e.g. Thornton and Sokoloff 1998; Trumper 2003; Sokoloff et al. 2007; Thornton 2008; Bernhard 2010; Sharma et al. 2010), but it is important to understand that the use of computers and other "high-tech" equipment is not a requirement for student learning. Indeed, simple materials are used in the *Physics by Inquiry* curriculum developed by McDermott and co-workers at the University of Washington (e.g. Shaffer and McDermott 1992; Wosilait et al. 1998). Furthermore, the use of probeware in mechanics labs does not necessarily lead to good learning results, and an instructional approach based on variation theory is also essential (Bernhard 2003, 2011). Similar conclusions concerning the use of probeware in electric circuit labs and electro-chemistry labs have been reported by Carstensen (2013) and Ling and Marton (2012), respectively. Crucial aspects of the technology used are not its simplicity or complexity, but the opportunities (and constraints) for discernment and (hence) learning it affords. It is the responsibility of the teacher to use these possibilities in a constructive way by carefully designing tasks that help students to discern the critical aspects of the object of learning. Thus, belief in technological determinism is fallacious.

Technological determinism is related also to the second research question, regarding the relationship (if any) between the technology used and the actions of the students in the labs, i.e. their discourse. As mentioned above, the labs considered in this study were investigated *in situ*, i.e. in a naturalistic setting. It is possible that the students' discourses in the tape-timer and photo-gate labs would have differed if they had been instructed in a manner based on variation theory. I believe so, but with qualifications. As is summarized in Table 2 there would still have been specific limitations in the opportunities to introduce variations and the simultaneous experience that variation theory considers to be essential for learning would have been difficult to arrange. Nevertheless, results presented by Bernhard (2003, 2011), Carstensen (2013) and Ling and Marton (2012) show that students' discourses and lived objects of learning depend on the affordances of technology used, and on how well these possibilities are utilized by the teachers in their design of lab tasks and when writing lab instructions. Hence, while I contend that the answer to RQ1 is independent of the educational setting, since it is related to the inherent possibilities of the technologies, the answer to RQ2 may depend on the educational setting. Students' discourses may be slightly different in settings other than those investigated in this study. It is, however, still the case that the primary output of experimental data and the type of measurement (see Table 3) seem to influence students' discourse. More extensive observations of interactions in further settings are required before any conclusions can be drawn concerning the extent that a specific technology and other factors (for example, student background, nature of instructions given and task structure) affect the students' discourse.

Finally, the dependence of my conclusions on the theoretical framework should be considered. Although I have performed this study, and interpreted the results, within the framework of variation theory and philosophies of technology based on pragmatism and (post-)phenomenology, I maintain that most of my results and conclusions are valid also when regarded in terms of other frameworks. For example, my results show that some technologies do not permit the design of an experimental *predict–observe–explain* (POE) sequence (e.g. White and Gunstone 1992; Coştu et al. 2012) for the acceleration at the turning point (where the velocity is zero) when the travel of a cart changes from going up an inclined plane to going down. Similarly, some technologies do not permit the arrangement of "cognitive conflict" (e.g. Posner et al. 1982; Gorsky and Finegold 1994) or "conceptual conflict" (e.g. Hewson and Hewson 1984) in the same situation. Indeed, the lab to investigate motion in an inclined plane using probeware was designed using POE theory, according to Thornton (2008), while Haglund et al. (2015) have based thermodynamics learning tasks on POE-sequences. Furthermore, as experimental technologies as mediating technologies strongly influence *figure-background* relationships, i.e. through their *amplification–reduction*, *revelation–concealment* and *enablement–constriction* structures, their roles could be considered within a cognitive load framework (e.g. Chandler and Sweller 1991). For example, in this framework, it would suitable to analyse an actual technology's contribution to *extraneous* cognitive load suggested to be detrimental for learning (Chandler and Sweller 1991) or its enablement of *germane* cognitive load suggested to be useful for learning (Muller et al. 2008). It is beyond the scope of this paper to go further in detail how my results could be interpreted in other frameworks.

Implications

In the context of quantum physics, Bohr (1958) argued that "the word *phenomenon* [should] exclusively … refer to the observations obtained under specified circumstances, including an account of the whole experimental arrangement [and] it is … impossible to distinguish sharply between the phenomena themselves and their conscious perception". In a similar vein, textbooks used in the education of engineers and scientists, for example *Microscopy of Materials* (Bowen and Hall 1975), stress that an experimenter must ask "what can this instrument be used for, and which … is best for [a] particular problem?" Furthermore, Bowen and Hall stress that an experimenter must thoroughly understand the instrument and its "advantages and limitations". The results of this study show that Bohr's and Bowen and Hall's arguments are also valid for students' learning in labs in educational settings. For example, they demonstrate that it is difficult for students to "distinguish sharply between the phenomena themselves and their conscious perception". Indeed, the etymology of the word phenomenon comes from Greek *φαινόμενον* "thing that appears". However, as pointed out by Garfinkel (2002), you may "losing the phenomenon" due to the way an experiment is set up and the equipment used. This implies that researchers in science and engineering education, teachers, and educators of teachers must consider "which instrument is best for a *particular* object of learning", while teachers need to "thoroughly understand [the] advantages and limitations" of different labs and experimental technologies for student learning. Hence, we should avoid discussing learning in labs in general terms and draw general conclusions very cautiously.

Accordingly, this study shows that there is no general answer to the common questions: "Do labs really assist students' learning?" and "Are they worth the cost?". Their value for a *specific* object of learning depends on the suitability of the technologies used for *that* object of learning and on the design of the tasks in the lab. Neither can "real" labs be compared in *general* terms to "virtual" labs. For example, Olympiou et al. (2012) contend that virtual labs, but not real labs, allow quick repetition of experiments, relatively easy variation of experimental conditions and observation of phenomena that cannot be directly observed by the naked eye. However, this paper shows that some experimental technologies, such as probeware, also have these affordances. This confirms the main conclusion of this paper: that different experimental technologies have very different affordances, and one should draw general conclusions regarding the affordances of experimental technology very carefully. Moreover, this is also true for virtual technologies, as shown by, for example, comparisons of virtual experiments with and without touch sensory (haptic) feedback (Zacharia 2015). Thus, it is impossible to compare "real" and "virtual" experimentation as undifferentiated categories.

Furthermore, the view that experimental technologies have little cognitive value is tacitly expressed or implied in at least three recent reviews and books (Psillos and Niedderer 2002; Singer et al. 2006; Lunetta et al. 2007). This can be understood in the light of the review presented earlier in this paper and the view that experimental data are simply "observables" (Hempel 1952). However, the technologies used in laboratories, and their suitability for the application, have not always been neglected. For example, considerable interest in teaching instruments for laboratories and demonstrations arose around 1800, but after WWII they "were just considered cumbersome, obsolete and useless artefacts" (Brenni 2010). This paper highlights the need to revive the interest in equipment as "teaching instruments", but in a modern way informed by, for example, variation theory. This paper and my earlier research (for example, Bernhard 2008) indicate that the technology used in successful labs brings important concepts and relationships into students' focal aware-ness by enabling constructive patterns of variation to be observed and discerned. In such cases, the technology is a "cognitive tool". Furthermore, Tala (2009) has studied scientific practice in nanophysics as an example of techno-science, and argues that science education should be based on a "scientifically sound and authentic content [of science as] the necessary starting point", taking into account (among other things) the use of technologies. In a similar vein, several decades ago Gooding (1990) stressed that "theories of learning and representation should be compatible with our knowledge of how scientists gain and use information about reality". However, if we are not aware of the role of tools and technologies, and do not "thoroughly understand technologies and their advantages and limitations", we will simply, as Cuban (2001) notes "[use] the new technology to maintain existing practices" or do not question existing practices.

Conclusions

> The reason we are on a higher imaginative level [in modern science] is not because we have a finer imagination, *but because we have better instruments*. In science, the most important thing that has happened in the last 40 years is the advance in instrumental design…a fresh instrument serves the same purpose as foreign travel; *it shows things in unusual combinations. The gain is more than a mere addition; it is a transformation* (Whitehead 1963, my italics).

In previous sections I have demonstrated that "appliances of a technology [can be used as] tools of knowing" (Dewey 1925/1981), i.e. they have "cognitive value". However, as demonstrated by my examples of three experimental setups that initially seem to provide opportunities to see the same physical relationships, different technologies can have very different cognitive values.

Several conclusions can be drawn from this study. First, the use of labs and experiments in education cannot be discussed in general terms. Instead, science education researchers, teachers and teacher educators need to specifically consider "which instrument is best for a particular object of learning". Thus, teachers and educational developers need to "thoroughly understand experimental technologies and their advantages and limitations" for students learning a specific content or specific concepts when planning teaching and design learning environments (cf. Bowen and Hall 1975). If new and old technologies are used in clever ways, we may achieve not only gains, but also transformations in students' learning.

Furthermore, my study shows that there is no general answer to the common questions regarding whether labs really assist students' learning and whether they are worth the cost. Further, real labs cannot be compared in general terms to virtual labs. We should discuss learning in labs in general terms and draw general conclusions very cautiously.

Roth and Jornet (2014) have recently argued, with special reference to Dewey and Vygotsky (and others), that the term "experience" is undertheorized in science education research literature. Indeed, the use of tools (i.e. artifacts/technologies) plays an important role in both Vygotsky's and Dewey's theories of experience and action (e.g. Vygotsky 1978; Dewey 1938/1986; Cole 1996; Hickman 1990; Miettinen 2001; Cole and Derry 2005). My conclusion is that the role and use of technologies in science education is also undertheorized. I argue here that the role of technologies extends far beyond the use of computers, and their roles in the laboratory remain a neglected aspect of research in science education that warrants richer, more detailed investigation, and better theorizing.

Barad (2003), a theoretical physicist by training, argues that we must let matter matter. "To think of discourse as mere spoken or written words forming descriptive statements is to enact the mistake of representationalist thinking. Discourse is not what is said; *it is that which constrains and enables what can be said*" (ibid., my italics). Paraphrasing Barad, I contend that "discourse is not what is said; it is that which *constrains and enables* what can be said, done and *discerned*". I have demonstrated in this paper that the technology used in labs constrains and enables what can be discerned and ultimately learned.

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