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Virtual Educational Laboratories: Instructive or explorative learning?

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DASTS is the primary academic association for STS in Denmark. Its purpose is to develop the quality and breadth of STS research within Denmark, while generating and developing national and international collaboration.

Abstract

This paper explores how the field of Science and Technology Studies (STS) can inform and help conceptualise a relatively new form of laboratory work in education: virtual laboratories. To date, STS have not addressed laboratory work in education. This paper focuses on the virtual educational laboratory by synthesising arguments from the STS literature on laboratory work and proposes research questions that can guide future ethnographic research on how virtual laboratories are applied and constructed locally in the classroom. I argue that the virtual laboratory, like the physical one, must be understood in a broader cultural, social and material context. Moreover, the virtual laboratory has both constraints and affordances, tied to the medium through which it is materialised. I conclude that the virtual laboratory can be understood as a hybrid between explorative and instructive learning.

Introduction

Science and technology studies (STS) have been occupied for a long time with exploring how scientific facts and knowledge are produced in laboratories and how these affects and transforms society (e.g., Knorr-Cetina, 1992; Latour & Woolgar, 1979). For example, laboratory studies have been instrumental in demonstrating that cultural, social, and material factors are substantial for stabilising and producing scientific facts. Scientific knowledge is a product of a complex network of relations and artefacts, not natural 'givens' discovered by science (Latour, 1978; Pickering, 1995). This insight makes it relevant to study the production of knowledge concerning the laboratory. But STS have not explored the role of the laboratory in educational settings, which this paper addresses, and, more specifically, the use of virtual laboratories in education. By synthesising arguments from the STS literature on scientific laboratories, I suggest that STS can provide nuance and broaden the understanding of virtual laboratories in education.

Over the past years, a new kind of laboratory has emerged in education: virtual laboratories. Virtual laboratories are computer simulations in which pupils can explore and interactively engage with subject areas related to STEM[1] in a laboratory environment. These interactive simulations enable the pupils to actively change or define different parameters and observe the consequences of their actions. Virtual laboratories are primarily being used in universities and upper secondary schools (Lewis, 2014; Achuthan, 2018) but are used in lower secondary schools as well (Implement, 2018). This paper concentrates on the educational setting of lower secondary schools in Denmark, which is the empirical focus of my research. I have performed field work at three schools, where I have done video-based observations, screencast the pupils while they work with virtual laboratories and interviewed pupils and teachers.

There has been a political push to implement virtual laboratories in Denmark as a part of science teaching in lower and upper secondary

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[1] Science, Technology, Engineering and Mathematics

schools. The 'Action Plan for Technology in Teaching', published in 2018 by the Ministry of Education, states, 'Virtual simulations can increase pupil's motivation and learning in science. They can supplement the traditional (physical) experiments' (Undervisningsministeriet, 2018, p. 19). This goal is closely connected to a STEM agenda to increase the pupil's motivation and learning in science teaching. The Ministry of Children and Education has launched different initiatives to stimulate virtual laboratories in schools. One initiative involves free access to a selection of virtual laboratories from the Danish company Labster from May 2019 to June 2020. Furthermore, a development project with ten schools was launched in 2019 to experiment with and develop different didactic and technical approaches to integrate virtual laboratories in science teaching (Børne- og Undervisningsministeriet, 2019).

As stated above, there are different political expectations and aims regarding the use of virtual laboratories in education. STS scholar Estrid Sørensen (2009) argues that research should not focus on what we would like learning technologies to do, rather on how technologies form and change teaching practice in often unexpected manners. New learning technologies must be understood in the situated, social and material contexts in which they are embedded and should be studied ethnographically. The research field of virtual educational laboratories is primarily quantitatively oriented, e.g. it uses pre- and post-test or control groups. These studies focus on different matters, such as the impact that virtual laboratories have on the learning outcome or motivation, for example, in comparison to traditional teaching (Dyrberg et al., 2017; Makransky et al., 2016; Smetana and Bell, 2012; Vogel et al., 2006). This paper makes the case that there is a need for an ethnographically and STS-inspired approach to studying virtual educational laboratories to understand which situated educational practices come about.

In the first part of the paper, I propose distinguishing between four kinds of laboratories to conceptualise the understanding of laboratory work and highlight my contribution to STS. First, I argue that there is a significant difference between the laboratories used for scientific purposes versus those used for educational purposes. While the first is concerned with the production of knowledge, the second is concerned with replicating knowledge for learning purposes. When considering virtual laboratories in education, how knowledge is replicated becomes important. Inspired by learning theory, I suggest a distinction between a more instructive approach to learning and a more explorative one. The distinction is used to discuss and conceptualise which kind of learning is enacted with a virtual laboratory. Second, I distinguish between virtual and physical laboratories. While STS have traditionally focused on the physical laboratory, I pay attention to the virtual laboratory.

In the second part of the paper, I draw on and synthesise perspectives from the STS literature on laboratory work and experimentation and examine how these insights can propose research questions for further ethnographical research. First, I argue that the virtual laboratory, like the physical one, is a part of a broader socio-material network, such as the materiality of the classroom, interactions among pupils and teachers, teaching styles, etc. It is crucial to shed light on these networks to understand which learning situations are constructed with the virtual laboratory. Second, based on STS studies on computer models and simulations, I argue that one must pay attention to the role of the medium that virtual laboratories work through, i.e. the computer, and to which affordances and constraints the medium brings about. Third, the STS literature has demonstrated that mangling, mishaps, contingency and tacit knowledge are essential elements of experimental and scientific practice. All the hands-on mangling practice is left out in the virtual laboratory, and the knowledge is conceived utilising a simulated laboratory. It is vital to examine how the above-mentioned aspects of the physical laboratory work are affected when the experimental practice is moved to a virtual laboratory. Towards the end of the paper, I argue that the virtual laboratory can be conceptualised as a hybrid between explorative and instructive learning.

Four ways of distinguishing between laboratories

To nuance and specify the understanding of laboratory work, I make some distinctions to relate my contribution to the field of STS and laboratory studies. The first distinction is between the laboratories used for scientific purposes and those used for educational purposes. The fields of STS and laboratory studies have been engaged with scientific laboratory work and scientific knowledge production (Sismondo, 2010). However, they have not paid attention to laboratory work in an educational setting. A central distinction between these two kinds of laboratories is that scientific laboratory work is concerned with producing new knowledge. In contrast, laboratories in an educational setting are designed to reproduce established knowledge. This distinction is inspired by Estrid Sørensen, who argues that there is an essential difference between Bruno Latour's understanding of scientific and educational knowledge. Latour argues that knowledge is produced based on circulating references, such as diagrams, maps and samples, where this circulation establishes it as factual (Latour, 1987). Here, scientific knowledge is new because it is not yet established and must circulate to accomplish the quality of being knowledge (Latour, 1999). Hence scientific knowledge is new not only to the scientist but also to the science community and society.

In school, knowledge is already established as knowledge and is only new to the learner. The references that make up the knowledge in school are already accepted as valid, and learning is achieved when pupils connect to these references (Sørensen, 2009). The knowledge produced in and around laboratory work in an educational setting is connected to certain representations of knowledge and understandings of learning. In the educational laboratory, the purpose is to introduce the learner to established knowledge within teaching plans, curricula and other learning activities. This goal makes it relevant to investigate which learning situation the virtual laboratory creates and is embedded in to understand which kind of learning practice is enacted. It is important to note that the distinction between the two kinds of laboratories is not as strict as stated above. For example, some scientific laboratories are used for educational purposes, and, sometimes, established knowledge is reproduced in the scientific laboratory. Similarly, in educational laboratories, especially in higher education, new knowledge can be discovered and contributed to the scientific community. But the distinction is useful for defining and conceptualising the characteristics of knowledge production in education and science, respectively

The second distinction is between virtual laboratories and physical laboratories. The STS literature has been occupied, for the most part, with work conducted in a physical laboratory. Some scholars have addressed the entry of 'dry'[2] or 'virtual' laboratories in science and how this new laboratory setting affects the production of knowledge (Merz, 2006). However, the field of STS has not paid attention to the virtual laboratory in an educational context. The distinction between the two laboratories is not clear-cut. There are different 'virtual' or technological elements in most physical laboratories, including simulations, apparatuses and computer visualisations. The virtual laboratory is physically embedded in a learning situation and the interpersonal dynamics between pupils and teachers. But the central point is that the STS literature has focused the most on the knowledge production embedded in a physical laboratory and has paid less attention to the virtual laboratory. In other words, four central distinctions or quadrants can be constructed to conceptualise the different laboratories referred to in this paper, which are illustrated in the diagram below.

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[2] Dry labs are laboratories in which computers are used for data collection, modeling and simulation, in contrast to wet labs, in which various liquids and chemicals are tested and analysed.

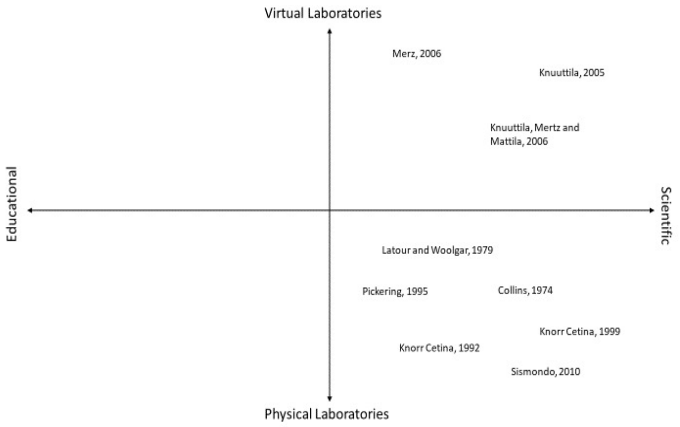

Diagram 1: Laboratories and the field of STS

Note. The diagram is visualised as a continuum where the arrows on the x-axis and y-axis indicate that a laboratory can be more or less on one side of the diagram. Examples of STS scholars focused on physical and virtual scientific laboratories have been inserted in the diagram.

While the field of STS has been occupied with the right side of the diagram, i.e. physical and virtual laboratories in science, the left side of the diagram, i.e. the virtual and physical laboratories in education, have been ignored[3]. This paper aims to shed light on the upper left quadrant, virtual educational laboratories.

The virtual laboratory in education

Virtual laboratories are computer simulations, which, as the name suggests, take place in a virtual context and are designed to give the user the experience of performing experiments in a laboratory setting (Jones, 2018). Virtual laboratories are a part of a broader field of computer simulations in science education. These simulations are defined as computational models of a physical phenomenon, where the user can change different parameters to observe the consequences of their actions (Clark et al., 2009). Simulations differ from static visualisation (e.g., an illustration in a textbook) because they are interactive (Plass et al., 2009). There are different nuances in the definitions in the research literature on interactive simulations, but a common thread is that it is not enough for pupils to observe a simulation; they must engage with it to achieve a better learning outcome (Stoney & Wild, 1998). The user must be able to choose or define actions in the simulation and observe the created sequence (Vogel et al., 2006).

However, how interactive the virtual laboratories are varies a great deal. Some simulations give the user concrete instructions, while others are more openly designed and call for a freer inquiry. Some simulations even allow the user to access the software system and remodel the simulation with an easy-to-use programming language (Honey & Hilton, 2011). In other words, the element of interactivity is broadly interpreted in practice. Furthermore, some are simple 2D visualisations, while others are 3D game-like simulations. In certain virtual laboratories, the emphasis on immersive and game-based elements is prioritised to create engagement and motivation (Jones, 2018). To illustrate the diversity in the field, I focus on two virtual laboratories used in science education: Physics Education Technology (PhET) and Labster. These are also the objects of my ethnographic study of science teaching with virtual laboratories in lower secondary school.

The University of Colorado Boulder developed PhET. It offers a large online library of virtual interactive simulations that are freely available for science education. The simulations are designed so that pupils and teachers can use them with minimal prior training (Honey & Hilton, 2011). Each simulation is designed to target a core science concept, such as wave physics. The pupils can create their own waves, watch how they interact in various ways, and learn about the basics of wave physics. The amount of freedom pupils have varies within the simulations. While some are quite open and allow the user to explore more freely, others

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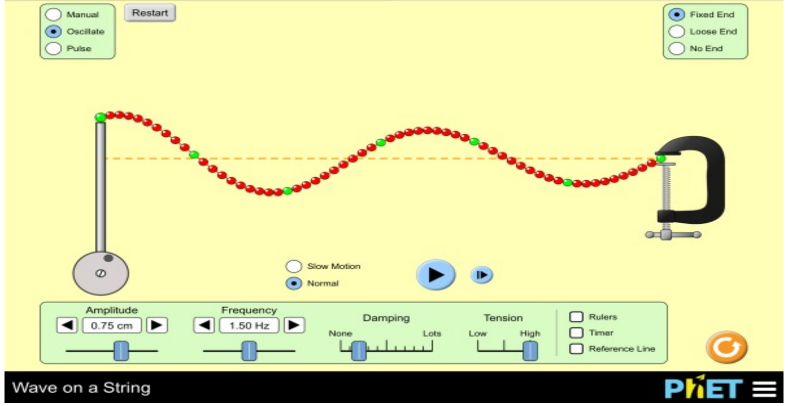
[3] STS scholars, such as Fenwich and Edwards (2010), have studied education and learning through an Actor–Network Theory (ANT) lens. Further, Sørensen (2009) has focused on the digital technologies, such as the online 3D virtual environment and weblogs, in education from a socio-material perspective. But these scholars have not addressed virtual educational laboratories.

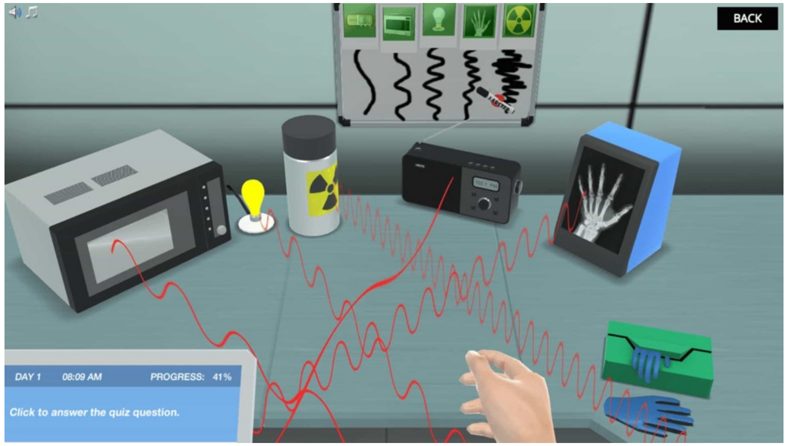
do not encourage much free exploration. The simulations have simple graphics and no specific focus on gamification elements (Jones, 2018).


○ Manual
● Oscillate
○ Pulse
● Fixed End
○ Loose End
○ No End
○ Slow Motion
● Normal
Amplitude 0.75 cm
Frequency 1.50 Hz
☐ Rulers
☐ Timer
☐ Reference Line

Note. https://phet.colorado.edu/en/simulation/wave-on-a-string. Illustration from the PhET Interactive Simulation, University of Colorado Boulder, 'Wave on a String' for Physics.

Labster was developed by a Danish company by the same name. It was primarily developed for upper secondary schools and universities but is also used in lower secondary schools. Like PhET, a large selection of virtual laboratories is accessible online, but schools need to buy a license to get access. There is a strong focus in Labster simulations on immersive or game-based elements, such as a storyline that the simulation is built around and a mission that the pupils need to fulfil to make it more engaging. The user can 'walk around' the laboratory, and when a procedure involves a physical act, they must be mimicked by the user, such as picking up a pipette, using it, putting it back, etc. Unlike PhET, there is a strong focus in Labster on making the user feel as though they are in a real laboratory (Jones, 2018).

The Labster simulations also include multiple-choice questions, and the pupil can read the associated theory to answer the questions. There is a scoring system in which the pupil gets a final score depending on how well he or she answers the questions. Labster simulations are quite story-boarded or instructive: the user is often guided through the technical steps for carrying out laboratory procedures by a voice-over. There are also experiments where the user can change the variables and experiment more freely, but the learning is still more guided than in PhET, which often allows for a high degree of freedom. In contrast, Labster simulations have a strong focus on creating an authentic laboratory environment, game-based elements and context around the experimental practice, which is not the focus of PhET.


DAY 1 08:09 AM PROGRESS: 41%
Click to answer the quiz question.

Note. https://www.labster.com/simulations/light-and-polarization/. Illustration from the Labster simulation 'Light and Polarization' for Physics.

Laboratory studies have not been occupied with learning since it is not the focus of the knowledge production conducted in scientific laboratories. But the notion of learning becomes a key focus when studying virtual educational laboratories, where the technology is intended to enhance and support learning. In order to conceptualise the virtual educational laboratory, the diagram below summarises four learning modes that can be said to characterise the virtual laboratory. I have inserted examples of the virtual educational laboratories used in upper secondary schools in Denmark. The diagram is visualised as a continuum where the arrows on the x-axis and y-axis indicate that the different virtual laboratories can be placed more or less on one side of the diagram.

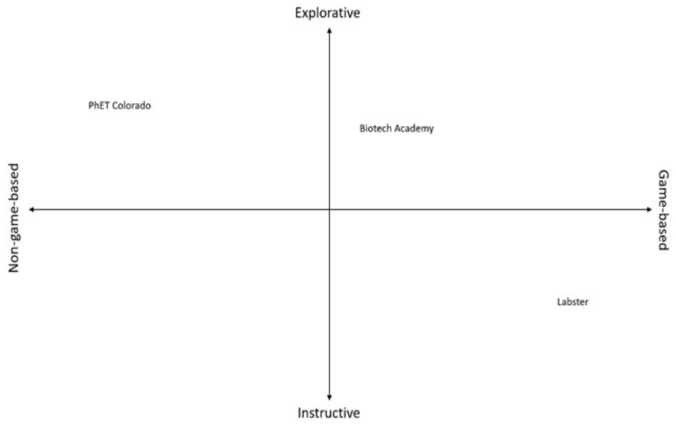


Diagram 2: Virtual laboratories and learning modes

Note. PhET Colorado, Biotech Academy, and Labster are the most frequently used virtual laboratories in lower and upper secondary schools in Denmark (Implement, 2018). The virtual laboratories designed by Biotech Academy are 3D laboratories developed for biology and biotech. Biotech Academy can be placed in a spectrum between PhET and Labster. The simulations are more instructive than PhET since the user needs to follow a predefined Experiment Guide. The Biotech Academy simulations offer a more open-ended space for actions than Labster, and they are less instructive but do not focus much on game-based elements.

Here, PhET can be placed on the upper left side of the diagram as explorative and non-game-based learning, and Labster on the lower right side as instructive and game-based learning. This characteristic is quite simplistic, and how explorative versus instructive PhET and Labster are is open for discussion. This issue is not the aim of this paper; rather, I argue that different designs of virtual educational laboratories are embedded in and constitute different learning modes. In this paper, I pay particular attention to the distinction between explorative and instructive learning.

Explorative and instructive learning

To develop my understanding of explorative learning, I draw on perspectives from constructivist learning theory. Philosopher of education John Dewey espouses the idea of learning as an affair of interacting with the world, as captured by Dewey's famous 'learning by doing' principle. By doing things, Dewey (1916) argues, we experience the consequences of our actions. One cannot know the world without being an actor in it, and it is through acting in the world, one obtains new experiences. In the Deweyan perspective, experience is understood as bodily and sensory experiences of the world in which one must interact directly with objects in practice (Brinkmann & Tanggaard, 2012). Because learning is essentially experience-based, teaching must focus on the pupil's active investigation and experimentation. Dewey divides experience-based learning into four stages: 1) sensing a problem, by being in doubt or frustrated, and starting to think about how to change it; 2) investigating the problem and formulating solutions; 3) reaching a conclusion based on the investigation; 4) testing and experimenting with the new knowledge. Learning, in this sense, is about active construction and participation instead of a passive transfer of knowledge (Beck et al., 2014). This focus on experiencing and doing is also the core concept of the central didactics used in science education today, such as 'inquiry-based science'. In inquiry-based science, the pupil explores and develops explanations for the phenomenon under investigation and evaluates their understandings by experimenting and observing (Gillies & Nichols, 2014).

Another source of inspiration comes from the mathematician and computer scientist Seymour Papert, who, in line with Dewey, puts active doing at the centre of learning. Papert focuses on the role of technology, especially the computer, as an important artefact for creation and participation. He sees computer technology as an effective and useful tool for constructing meaningful products (the 'doing' element) because computer technology has opened up new possibilities for creation (Papert, 1980), such as experimentation in a virtual laboratory. Explorative learning is now understood as a learning mode that focuses on the experience-based, active and free exploration and investigation of a scientific phenomenon. For example, this is the case when pupils in a virtual laboratory can experiment freely, observe the consequences of their actions and test hypotheses. In this regard, the focus is on open-ended experimentation, and the 'doing' element is highlighted' here.

The term instructive learning is inspired by the behaviourist theories of learning. In this context, learning is regarded as a causal connection between stimuli and response, where the learner's actions will be corrected or rewarded according to the correct response (Selwyn, 2011). The psychologist B. F. Skinner developed what he called 'teaching machines', which should engage the pupils and give them immediate responses. For Skinner (1958), the learning process is divided into several small steps, and the pupil reviews the feedback received after each step. This behaviouristic approach has played an important role in developing computer-assisted instructions (Selwyn, 2011). In relation to virtual laboratories, this mode of learning becomes particularly visible in step-by-step guidance, where the pupils are guided through the different steps in the experiment without much individual freedom. This kind of experimenting is more controlled, and there are 'rules' for what is desired or possible to do. Here, the focus is more on the transmission or acquisition of certain laboratory skills or procedures.

The divide between explorative and instructive learning is an analytic distinction used to illustrate a spectrum of learning modes that can help discuss which kind of learning virtual laboratories bring about. However, it is important to note that the learning process is far more complex than expressed by this divide. Different socio-material factors affect the learning situation, which will be elaborated upon in the paper. In the next section, I address what we know about laboratory work from STS and how these findings can help us conceptualise and nuance the understanding of virtual laboratories in education.

How is knowledge produced in a laboratory?

Early laboratory studies and the sociology of scientific knowledge (SSK) ask the central question: how are scientific facts made, and how are they made stable? The answer to this question is that the production of knowledge is essentially carried out socially and culturally. Scientific facts are not natural givens discovered by science but, rather, products of social dynamics. As Sismondo (2010) writes, '(…) decisions about claims are negotiated, a matter for different actors to decide through micro-sociological or political interactions' (p. 107). This point means that conversations and negotiations between scientists and other actors decide what is being established and communicated as scientific knowledge. What is stated as scientific claims cannot be predicted in advance, and the laboratory work must be studied through a cultural and social lens. In this sense, laboratory work and the production of scientific knowledge are no different from other interactions in our everyday life: they are just as messy and complex as any other social interaction (Sismondo, 2010).

In the second wave of laboratory studies represented by ANT, the material perspective of laboratory work is introduced. As Latour and Woolgar (1979) demonstrate in Laboratory Life, the laboratory becomes an important source for the construction of facts since the whole material setup in the laboratory enables the scientist to manipulate and arrange natural objects in certain ways. It is the social and cultural factors that are interesting in the construction of science and the equipment and technical instruments used in the laboratory, i.e. the non-human actors. As per this perspective, scientific claims are negotiations between different actors: materials, techniques, technologies, scientists, and others (Knorr-Cetina, 1992). The laboratory is an association machine that establishes connections between different entities.

Latour and Woolgar (1979) illustrate how natural objects and phenomena are translated into figures, numbers, graphs, etc., via inscription devices, which are the different instruments and apparatuses used to produce data about the object and phenomena in question. Furthermore, these inscriptions are translated into scientific claims. Laboratory studies show a discrepancy between what the textbooks say makes science valid and how science works in practice. As Merz (2006) writes, 'In this perspective, knowledge production is closely associated with the laboratory as a site of locally embedded practice' (p. 157). These studies make it scientifically relevant to shed light on how the order is produced out of the seemingly messy network of things and actions (Latour and Woolgar, 1979; Pickering, 1995). Which learning situations unfold around virtual laboratories should therefore be empirically questioned. The distinction between entities cannot be made a priori (Latour, 1987) but must be made based on the connections between human and non-human actors constructed locally in the classroom. How this plays out in a context with computer simulations will be further elaborated below.

The rise of dry or virtual laboratories

In recent years, a new kind of laboratory has emerged in the production of scientific knowledge: 'dry labs' and 'virtual laboratories'. The field of STS has raised the questions 'How do computer simulations influence the production of scientific knowledge?' and 'Does the computer simulation bring about a new way of doing science?' (Knuuttila et al., 2006; Merz, 2006). One response to these questions is provided by Merz (2006), who investigates the use of computer simulators in particle physics. She argues that scientific practice in a virtual laboratory is just as messy and complex as work in physical laboratories. The simulation activities are embedded in a wider material and social network and are entangled with 'other endeavours in experimental physics, theoretical physics, or other fields of practice; the relations, rankings, and hierarchies of different data types; and so forth' (Merz, 2006, p. 166).

Thus, instead of understanding the virtual laboratory as a delineated practice, it must be understood as being intertwined in a broader network of things, understandings and actions. The learning situations that will be created cannot be predicted by reading the teacher guidelines or lesson plans. The use of virtual educational laboratories must be studied as being embedded in a broader sociocultural and material context. When studying these laboratories, we need to ask how the sociality and local cultures in the classroom, such as teaching styles and interactions among pupils and teachers, affect and form the use of virtual laboratories. For example, the framework and guidelines provided by the teacher play a central role in a concrete learning situation. In my pilot study, the teachers provided different guidelines for how pupils should interact with the virtual laboratory. These included providing questions related to the simulation, letting the pupils work in pairs and participating in follow-up discussions in class. In this way, the teacher counteracts some of the more individualised and instructive elements when working with virtual laboratories in education. In other words, technology makes some understandings of learning easier or more difficult than others. However, it is essential to investigate the situated empirical context around the use of virtual laboratories. Moreover, a material perspective must be adapted to investigate how learning situations are constructed in a network of both human and non-human actors. A question to ask from a material perspective is how the technology brings about a certain ordering of things that affects the learning situation (the role of the medium), which will be discussed in the next paragraph.

Affordances and constraints of the virtual laboratory

STS scholars Knuuttila and Voutilanien (2003) have examined the use of computer models in science. They argue that the models must be understood as material artefacts and not just as an abstraction or concept. They define the models as 'epistemic artefacts': that is, 'as intentionally constructed things that are materialised in some medium and used in our epistemic endeavours in a multitude of ways' (Knuuttila, 2005, p. 1266). It is especially important to consider the media through which models are materialised and pay attention to their affordances and constraints, which are often tied to the medium through which they work. As materialised things, models are not open to all possible uses and understandings.

Furthermore, a model is not representative in and of itself but will be interpreted and unfolded in multiple ways when implied in a specific context. This perspective allows actors to hold different conceptions of the same artefact and serve multiple purposes (Knuuttila, 2005). Like computer models, virtual laboratories are tied to the computer and representation through computerised algorithms (the medium). Consequently, virtual laboratories will always be constrained by how they are programmed and designed. The virtual laboratory is configured and programmed according to existing knowledge or theory associated with the field. There are rules or limitations for actions in a simulated world, and exploration done in a virtual laboratory will never be as free as that in a physical laboratory, where the range of possible outcomes are endless. Therefore, one could argue that the virtual laboratory work cannot be fully explorative: it will always be instructive or controlled to some extent due to the medium through which it is materialised.

Virtual laboratories can be compared with flight simulators to illustrate this perspective. Simulations in aviation have been used for a long time since the novice pilot needs a safe environment to learn how to fly without putting himself or others at risk (Aebersold, 2016). The flight simulator is not designed to accumulate new knowledge but to imitate the real experience of piloting an aeroplane. Here, the pilot can learn from his mistakes without real danger and repeat the simulation until he is good enough to fly a real aeroplane[4]. But it is when the pilot flies in a real aeroplane, he will discover new knowledge that is not a part of existing theory or perception of the world.

As with pilot training, the use of virtual laboratories provides the opportunity for pupils to interact with processes that otherwise would be too dangerous or impossible in the physical laboratory. Virtual laboratories in education are often used as a supplement or a rehearsal for physical experiments and a safe training environment in which the pupils can learn from their mistakes and refine their skills (Honey & Hilton, 2011). But the medium implies an epistemological problem. On the one hand, the virtual laboratory gives the pupils a sense of hands-on experience by simulating the experience of being in a laboratory, mimicking the working procedures, interacting with materials and apparatuses, etc.

On the other hand, the practice in the virtual laboratory is essentially not a hands-on experience, but a simulation of a reality wherein the pupil's actions are mediated by a computer. In my pilot study, the pupils experienced or sensed that the physical interaction with the materials was essential to their learning; as one pupil put it, 'It is easier to incorporate when it is physical (…). I think that it matters that you are actually doing it and not just clicking with this one [the mouse], and then it falls down in this one (…), but it is something I do myself' (Interview Anna, 26.08.2020). The direct interaction with objects in practice is essential to experienced-based learning, as described by Dewey, which can be said to be problematised with virtual laboratories. So, the medium (the computer) possesses both essential affordances, such as a safe training environment, and constraints and limitations to possible actions and discoveries. In the next section, I turn to the STS literature on the epistemology of experimental practice and how these perspectives can inform and conceptualise our understanding of virtual experiments in education.

The (unnatural) experimental practice

There is a long tradition in STS of dealing with the relationship between experiments and laboratories (Knorr-Cetina, 1992; Sismondo, 2010). Shapin and Schaffer (1985) unfold the concept and role of experimental

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[4] There are also other areas in which simulations are used for training purposes, such as in health education (e.g., training for surgery) and military training (e.g., war games) (Aebersold, 2016).

practice in modern science. They investigate the controversy between chemist Robert Boyle and philosopher Thomas Hobbes over Boyle's experiment with an air pump in the seventeenth century. Boyle's experimental practices can be regarded as the beginning of modern science, where phenomena are taken out of their natural environment and isolated in a laboratory context: 'proper natural philosophical knowledge should be generated through experiment and the foundations of such knowledge were to be constituted by experimentally produced matters of fact' (Shapin & Shaffer, 1985, p. 22). By performing experiments, it becomes possible to replicate and validate the results. Hobbes was very sceptical about this practice and denied that experiments done in an artificial setting, such as in a laboratory, could lead to scientific facts. Despite Hobbes's opposition, Boyle's experimental paradigm eventually became the beginning of modern laboratory experimental practice. Experiments came to be seen as a phenomenon where natural objects could be isolated, manipulated and observed.

Knorr-Cetina (1992) unfolds this relationship between the experiment and the laboratory. STS has shown that the experimental practice in the laboratory 'rests upon the malleability of natural objects (…). In fact, laboratories rarely work with objects as they occur in nature' (p. 116). In the laboratory, scientists work with for instance visualisations of objects, isolated components and extractions – in other words, purified versions. Knorr-Cetina identifies three central features of natural objects that are changed when working in the laboratory. First, laboratory science does not need to work with the object as it is. Second, the scientist does not need to work with the object where it is (i.e., in nature) but can bring it home to the laboratory context. Third, the scientist does not need to attend an event when it happens; they can speed up a natural process or make it happen more frequently (Knorr-Cetina, 1992). The epistemological advantage of the experiment is that it does not need to accommodate objects within a natural order and the scientific phenomenon can be investigated in a controlled and manipulated laboratory setting.

Enhanced purification and manipulation?

With these characteristics of the experiment in mind, it is time to discuss experimental practice in the school. In a school setting, one could argue that the field studies related to observing, for example, insects or fauna in nature, are as close as we get to Hobbes's understanding of investigating scientific phenomena in their natural environment. But most scientific practice in schools is performed as experiments in laboratory settings, where the pupils conduct small experiments in groups (Hodson, 1990). Here, the scope of the experimental practice is to (re)produce scientific facts or established knowledge in a controlled environment or, as Knorr-Cetina (1992) puts it, using a purified and malleable version of the natural object.

In the virtual laboratory, one could argue that natural objects become even more purified since the objects are not physical but virtual representations. When the experimental practice occurs in a virtual and programmed setting, the reality can be adapted to specific learning outcomes. Virtual laboratories can be designed to simplify learning by removing confusing details and focusing on core elements (De Jong et al., 2013). As illustrated earlier, as a computer-programmed object, the virtual laboratory enables a learning setting that is safe and designed for specific learning outcomes (affordances). However, it also limits the range of actions and possible outcomes (constraints).

Furthermore, the virtual laboratory offers efficiency since processes can be sped up without authentic delays, and the pupils can experience photosynthesis with one click of the mouse. In other words, restrictions of time and space are abolished in the virtual laboratory. As we can see, it becomes empirically relevant to investigate how the features of the virtual laboratory affect the learning situation in multiple ways. In the next section, I unfold the concept of tacit and embodied knowledge and discuss how this kind of knowledge might be affected by experimentation in a virtual setting.

Tinkering and tacit knowledge

Even though experiments are set in a manipulated and 'designed' environment, laboratory work is not as smooth as one might expect. Hacking (1983) argues that 'laboratory work is not merely about representation but about invention' (Sismondo, 2010, p. 108). The scientist is actively engaged in manipulating the object because materials do not behave as one expects, apparatuses do not work, etc. Thus, laboratory work is indeed about tinkering (Knorr-Cetina, 1981) or bricolage (Latour & Woolgar, 1979) in order to make disobedient materials act how we want them to act (Sismondo, 2010). Here, the embodied and tacit knowledge becomes important to create successful scientific procedures (Knorr-Cetina, 1992). Collins (1974) argues that not all knowledge travels easily. In his study on the transfer of knowledge about building a TEA laser, Collins shows that no scientist could build the laser by only following a manual: the passing on of skills from an experienced informant is essential to building a functioning laser. He argues that some knowledge is essentially tacit. The transfer of knowledge requires a socialisation process (or is enculturated) in opposition to 'algorithmic' knowledge that can be formalised and standardised and, thereby, travels more easily (Sismondo, 2010).

In physical laboratories, the pupils interact with real materials, apparatuses and chemicals, and the tinkering component is essential to the outcome of the experiment. For example, it can be crucial if the pupil adds a little too much acid, heats something for too long, etc. Here, pupils encounter real errors, failures and unexpected results since they cannot just redo it, as is the case in the virtual laboratory (Tho & Yeung, 2018). The pupils also articulated this lack of real errors and mishaps in the pilot study. They claim that they are more focused when doing experiments in a physical laboratory than in a virtual one since their actions are irreversible and have real consequences. As one of the pupils said, '(…) In here [in the virtual laboratory] you know you cannot do it wrong, but in there [the physical laboratory] you need to focus in another way, because you do not want to spill sulphuric acid all over' (Interview Astrid and Simone, 20.02.20). This situation makes it interesting to further investigate how the lack of real errors and irreversible consequences affect the learning situation.

Moreover, in physical experiments, pupils are faced with unexpected events, such as measurement errors, whereas 'in virtual laboratories, students are not distracted by aberrations in the equipment or unanticipated consequences' (De Jong et al., 2013, p. 306). The tinkering element is essential for acquiring a practical knowledge of how materials and objects behave in unexpected ways. But even though pupils in the virtual laboratory interact not with physical materials but virtual representations, one could assume that there is just as much 'tinkering' going on in virtual laboratory as in the physical one; it is just another kind of tinkering. When pupils are working with virtual laboratories, they interact with the medium, such as the computer, the mouse and so on. Furthermore, they navigate through the laboratory mediated by the medium. In this sense, the pupils interact with the virtual laboratory in a double sense – both in the laboratory and with the laboratory (i.e. the technology that allows it to function). When investigating educational practices involving virtual laboratories, it becomes interesting to explore how embodied, or tacit knowledge becomes important for creating successful learning situations. Since knowledge cannot be transferred easily, what kind of tools, guidelines, skills and social interactions are needed to allow knowledge to travel into the classroom and beyond when working with virtual laboratories?

Discussion and concluding remarks

This paper offers an investigation into the virtual educational laboratory based on perspectives from the STS literature on laboratory work and my ethnographic pilot study. In contrast to virtual scientific laboratories, I have argued that virtual educational laboratories are concerned with established knowledge instead of producing new knowledge. In education, the focus is on learning already established knowledge with specific learning goals. Therefore, the focus shifts from a scientific production of knowledge to a learning perspective. Moreover, I point to a continuum between explorative and instructive learning, which is inspired by the constructivist and behaviourist learning theories. This distinction allows for a discussion of which learning modes are constructed and made possible with virtual laboratories. Even though virtual laboratories are shaped by different design principles and understandings of learning, as illustrated using Labster and PhET, there are some shared characteristics of the virtual laboratory.

Based on insights from STS studies, the paper makes the case that virtual laboratories, like the physical ones, must be understood as being intertwined with a broader network of social and material relations. We have learned from laboratory studies that actual knowledge production is always far messier and more complex than what the textbooks tell us. This insight also applies to the study of virtual laboratories in education, where learning must be understood in the situated, social and material contexts in which the learning practice is embedded, such as lesson plans, curricula, teaching styles, the materiality of the classroom and so on.

Moreover, STS scholars Knuuttila and Voutilanien (2003) argue that models must be understood as intentionally constructed things that can be used and understood in multiple ways. It is especially important to pay attention to the medium through which they are materialised and which affordances and constraints are tied to the medium. When studying virtual laboratories, we need to investigate how the medium through which it is materialised, i.e. the computer, implies some constraints and affordances. On the one hand, the computer can expand the scope of actions in science teaching. It allows pupils to conduct experiments and take actions that would not be possible in real life because they are too dangerous, expensive or just impossible to do so. This point is often stated as one of the great advantages of virtual laboratories (Honey & Hilton, 2011). For example, pupils can take a sample from Mars and go back and analyse it in the virtual laboratory, or they can get close to micro-biological processes that are not possible to observe in real life.

Moreover, the virtual laboratory offers efficiency since natural processes can be sped up, and the restrictions of time and space are abolished. In this sense, the virtual laboratory enables the exploration of problems and concepts in a way that would not have been possible in the physical laboratory. It also becomes more effective to do experiments in the class since the virtual laboratory does not require the pupils to find the materials, set up the experiment, etc. Furthermore, the virtual laboratory makes it easier to work with specific and delineated learning objectives because it is possible in a virtual environment to isolate a part of a natural phenomenon or work with specific elements of an experiment. In this context, learning can be targeted, and some more complex matters can be simplified to be made more understandable for pupils.

But there are also some constraints related to virtual laboratories that need to be addressed. When pupils are conducting experiments in a virtual setting, they encounter more purified versions of the objects. They do not experience the contingency, mishaps and errors – the tinkering element – that is essential to get a practical understanding of how materials, objects and apparatuses behave in a physical laboratory, as STS studies have demonstrated. In the virtual laboratory, pupils do not experience the lack of smoothness of the physical experiment, i.e. when the apparatus suddenly does not work, or a tube is too small and so on. One could argue that the learning with virtual laboratories become too smooth: the pupils do not experience the valuable feeling of frustration and the process of understanding why things are not working as expected.

Moreover, pupils do not interact physically with the materials and miss the tactile and physical elements of doing experiments. The hands-on interaction with objects and the experience of frustration and unexpected discoveries are essential to acquiring new knowledge within experience-based learning. In the two versions of virtual laboratories described in the paper, Labster and PhET, the problem and the learning outcome is formulated in advance. In Labster, the simulations are often built around a mission, so the element of problematisation and inquiry is incorporated into the simulation. But the inquiry is not based on the pupils formulating a hypothesis from their own musings and interactions with the world, which again is at the core of experienced-based learning. Other more open-ended simulations, which allow the pupils to access the software system and re-design or code the simulation, can be more explorative and supportive of creation and participation, as Papert advocates. However, the simulation is still tied to the restrictions of how it is programmed and is a representation of reality.

The virtual laboratory can be understood as a hybrid between explorative and instructive learning. In the virtual laboratory, some of the central elements of the experimental physical practice are removed, as stated above. The pupils interact with representations or visualisations of objects and do not learn the craft or practical skills of experimenting in a physical laboratory. The pupils experience tinkering in the virtual laboratories and interact both with (the medium) and in the laboratory. But it is another form of tinkering than the hands-on interaction with the objects in the physical laboratory. Experience-based learning is simulated, and the practice of experimenting is translated into a virtual setting, which is another form of learning practice.

On the one hand, one could argue that the virtual laboratory cannot be a fully explorative practice due to the medium; on the other hand, virtual laboratories can be both designed and used in more explorative manners. Further, compared to other learning materials, such as textbooks, static illustrations or videos, the virtual laboratories offer a more interactive and explorative approach to learning. Moreover, the virtual laboratory allows for exploring phenomena and discovering processes that only are made possible because of the medium, e.g. working with and exploring cells or atoms. In this sense, the virtual laboratory can be a hybrid between instructive and explorative learning.

To give a more nuanced and comprehensive answer regarding which learning situations come about with virtual laboratories, they must be understood as being embedded in a wider cultural, social and material context. Even though technology is intentionally constructed, the situated learning practices with virtual laboratories cannot be predicted. Which network revolves around the use of virtual laboratories is fundamentally an empirical question. In other words, educational virtual laboratory practices must be studied ethnographically in the local cultural context in which they are used. Therefore, it is essential to study how learning is constructed around virtual laboratories and how it plays out in the classrooms. How does the sociality in a classroom affect the use of the virtual laboratory? Is it so strong that it leads to using the virtual laboratory in other ways than the originally intended use of the technology? Or does the virtual laboratory have such a strong agency that it forces a specific ordering in the classroom? And how can tacit and embodied knowledge travel in learning situations with virtual laboratories? Questions like these are important to address in more in-depth ethnographical studies, where the sociality and materiality around virtual laboratories are explored and unfolded..

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