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Learning and the variation in focus among physics students when using a computer simulation

Abstract

This article presents a qualitative analysis of the essential characteristics of university students' "focus of awareness" whilst engaged with learning physics related to the Bohr model with the aid of a computer simulation. The research is located within the phenomenographic research tradition, with empirical data comprising audio and video recordings of student discussions and interactions, supplemented by interviews. Analysis of this data resulted in descriptions of four qualitatively distinct focuses: Doing the Assignment, Observing the Presentation, Manipulating the Parameters and Exploring the Physics. The focuses are further elucidated in terms of students' perceptions of learning and the nature of physics. It is concluded that the learning outcomes possible for the students are dependent on the focus that is adopted in the pedagogical situation. Implications for teaching physics using interactive-type simulations can be drawn through epistemological and meta-cognitive considerations of the kind of mindful interventions appropriate to a specific focus.

Introduction and background

In a research and development project concerning the use of computer simulations in physics education at university we (the authors) were considering the pedagogical value of basing a tutorial on a simulation of the Bohr model of the atom that included introductory spectroscopy in relation to energy levels. Despite having taken into account the results from contemporary research concerning physics education and/or computer simulations, we found that we lacked pedagogical insights into possible ways in which the students might experience the simulation, the pedagogical situation and associated potential learning outcomes. Thus we undertook such a research investigation.

Research in the field of physics education has pointed to some weaknesses in much of traditional physics instruction (see for example Redish, 2003; Redish & Steinberg, 1999); for example passiveness imposed on students, focus on reproduction and formulae (in contrast to problem solving, model construction/interpretation and relationships between variables). For specific concepts there are numerous studies on students' difficulties and conceptions (for an overview see for example McDermott & Redish, 1999), for example concerning the atom and the Bohr model (Budde, Niedderer, Scottand & Leach, 2002; Kohl & Finkelstein, 2005, 2006; Unal & Zollman, 1999). Another line of insight comes from general investigations into how students learn physics (for example Prosser & Millar, 1989), general ideas on how students view what physics is about (epistemological aspects: Hammer & Elby, 2003) and the validity of the description of "reality".

Computer simulations (and Computer Assisted Learning in general) have during the last decade been pointed to as a solution to many pedagogical problems and in particular as a remedy to student passiveness in physics education (for example Christian & Belloni, 2001; Esquembre, 2002; McDermott, 1990). However, despite the many projects developing various simulations and explicating a range of pedagogical approaches, we have found few attempts to bring about an understanding of what students' learning experiences in physics relying on simulations might look like. Studies that have examined the pedagogical value of simulations have done so mostly by utilizing measures of student learning outcomes (see also Gandole, 2005), for instance, by looking at conceptual change, (for example, Hewson, 1985; Tao & Gunstone, 1999; Zacharia & Anderson, 2003) or achievement tests (for example, Brungardt & Zollman, 1995). Two exceptions are Laurillard (1992; 2002) and Lindström, Marton, Ottosson and Laurillard (1993), originating from the same project, where they had the goal to understand better the development of conceptual and intuitive understanding of mechanics and electrical engineering students when they had to model and explore basic phenomena using specially designed simulation programs.

The investigation and analysis we carried out can be seen to be in line with the original ideas in the "approaches to learning" investigations (Marton & Säljö, 1976). In contrast to the more generic approaches to learning investigations (for example Marton, Beaty & Dall'alba, 1993; Prosser & Trigwell, 1999; Ramsden, 2003), we were more interested in the specific characteristics of what the students focused their awareness on and how the students created a "relevance structure" in the particular kind of pedagogical situation they were in. To stress this interest we identified the object of analysis to be the "focus of awareness", as constituted by students during their engagement with a computer simulation of the Bohr model. It is akin to approaches to learning but localised to this pedagogical situation – a simulation-based tutorial – having a particular stress on how elements of the simulation are intertwined in their experience and what the simulation's function is taken to be. It can be noted that while we investigate the "how" of how the students approach this situation, we have not dwelled on the "what" of the students' learning.

The results we report on in this article are of interest for physics teachers in that they offer insights into

- how computer simulations used in teaching physics at university may affect students' learning.
- ways of understanding the students' actions and dialogue, and ways of finding appropriate responses for supporting meaningful learning

Methodology and method for the study

The conceptual and analytical framework used in our research stems from the phenomenographic research tradition, a qualitative educational research approach that aims to capture variation in terms of qualitative differences in the ways in which people experience particular phenomena that constitute part of a pedagogical situation, be it subject content, approach to the learning task, or some aspect of the context (Marton, 1981, 1986). Research in this tradition seeks to offer interesting insights into important questions of student learning, in particular, what qualitative variation can be discerned when students tackle what we want them to learn (Marton & Booth, 1997). Phenomenographic research strives to analyse and describe learning from the perspective of the learner, making sense of the differences that are seen to be critical for learning. As such, it is an approach that is particularly appropriate for elucidating the design and implementation of teaching initiatives, such as simulations.

This study is based on a collaborative series of case studies involving first year physics students, 12 from a South African and 6 from a Swedish university[1], using the same procedure. Students were individually approached to be volunteers, participating on the premise of developing instruction and trying out a simulation, and they possessed a wide range of general physics knowledge and computer literacy (the South African and the Swedish group differed on average in both these respects). Audio and videotape recordings were made of pairs of students as they proceeded to work through a computer simulation (further described in the Results section) dealing with the Bohr model of the atom, which had already been covered in all the students' programmes of study to a reasonable level for the simulation to be meaningful. They were asked to respond to six predictive tutorial questions that accompanied the highly interactive simulation. Once they had finished (after 25-45 minutes), the pair of students was joined by one of the researchers for a discussion (15-40 minutes) in which they were encouraged to ask questions and seek clarification around that which they had been trying to make sense of during the simulation. The discussions were in research terms open ended interviews, exploring students' experience of the tutorial, their learning around specific aspects of Bohr's model and in particular their experience of the relationship between the simulation, physics and "the world". Students were commonly referring back to discussions and thoughts they had had while working with the tutorial.

One significant methodological stance taken in phenomenography is that the researchers strive to see the phenomenon as their informants see it – at the individual level when collecting data and, in all its complexity, the researchers also work at a collective level when undertaking its analysis and reporting. Data is collected to reflect the ways in which students relate to the contents, acts or contexts of learning. Most often it is the interview that is employed as the data collection method (Bowden & Walsh, 2000). But, as in this study, we can use students' natural conversations and acts as data, in as much as they reflect the experience of the learning situation in its various aspects.

Data analysis proceeded in the following manner. Initially, it was seen that in different extracts of the student dialogue they were expressing qualitatively different experiences of the situation, focusing on very different features of the pedagogical situation as well as the simulation. As the phenomenographic analysis proceeded in a systematic but non-algorithmic way the meaning of these different focuses became the topic of discussion between the authors. These extracts were examined in the light of the data as a whole, seeking other extracts with similar or different meanings. In practice the first key extracts functioned as seeds in a crystallisation process, so that a set of categories was formed. In the process, the categories were questioned in light of both one another as they were emerging and in light of newly accumulated extracts, leading to increasingly distinct descriptions and distinctions. Finally, the categories and extracts were checked for full data coverage by two authors independently in order to ensure "reliability" of the data-category relationship. It is nevertheless important to note that the point of the results (and thus their "validity") is not determined by the classification of data in categories as such, but by the quality and stability of the description of the categories and its value in similar pedagogical situations.

[1] *The instructional development was done as a cooperative project involving the physics departments at the South African and the Swedish university and similar data collection was done at both universities at different stages of the project. Since the core of the students' experiences was judged to be structurally similar in their range of variation, the two "pools of data" were joined for the purposes of the analysis reported here.*

One important component in the quality of the research outcome is the quality of data in relation to the described object of analysis. It is important that the actual research object is common to all the people who generate the data – the students who discuss the Bohr model of the atom in this case – and that there is no danger that they are in fact speaking of quite (or rather) different phenomena. This presupposes that the data is generated in such a way that the object of research is present to experience in one way or another – here as the computer representations of the salient aspects of the Bohr model. Ideally the essence of the actual research object is articulated in terms of a delimited and well defined phenomenon. Such a description is often done by referring to physics phenomena such as force, friction and heat or terms such as approach, learning, and focus of awareness.

When the categories were stable and distinctively described, there followed an analytical step, where the aim was to further explicate the nature of the categories (i.e. their structural and referential (meaning) aspects), following Marton and Booth (1997). Looking at the full collection of extracts and our description of the categories made in our analysis, we identified two themes that were determinant for the qualitative distinctions, both mainly related to the referential aspect. In practice the process can be described as identifying (in this case) two questions, which we (analytically) asked the pool of data: "Given this way of experiencing, what is the nature of physics knowledge implied?" and "Given this way of experiencing, what is the view of learning physics implied?". An overview of the results of this process is given in Table 1, in the beginning of the Discussion.

It is important to note that in this study the categories refer to the ways in which the object of learning was constituted in the dialogues between the student(s) and the researcher; or between the pairs of students, both with and without the researcher present; and thus is related to the situation as constituted and not to the individuals. Hence the focus-of-awareness categories themselves do not describe qualities of individuals or of pairs, but rather the approach they were moved to take as they experienced (in this instance) the computer simulation. Shifts might be seen within a single session, as the students gained insight into their situation, or actively decided on a new track for their work. Furthermore, it is accepted that individual students might have taken different approaches had they been working individually, rather than in pairs.

Results

The analysis led to the identification of four qualitatively different categories of the focus-of-awareness when engaging with given physics computer simulations. These are as follows:

- Doing the Assignment
- Observing the Presentation
- Manipulating the Parameters
- Exploring the Physics

Since each category is constituted across the whole of the pool of meaning, the illustrative extracts are chosen to highlight significant features of the way of experiencing the physics computer-based simulation. No single extract, therefore, can do justice to the whole category and no individual participant can be assumed to contribute to only one category. In order to ensure students' anonymity, the labelling of students in terms of (A) and (B) has no relationship from illustrative excerpt to illustrative excerpt. The only significance lies within an excerpt as a way of differentiating between individual students' descriptions.

Doing the Assignment

Constituting a focus on *Doing the Assignment* in the simulation session implies being concerned mainly with the constraints and features of the situation as an assignment that needs to be completed. External demands and expectations dominate the students' experience, while the simulation and the phenomenon it represents are, with respect to meaning, barely discerned at all.

In the example given below, two students are interacting with the Bohr model see a simulation (taken from van Heuvelen & D'Alessandris, 2000; a picture of the simulation window is shown in Figure 1; a simulation with similar topic of the Bohr model featuring energy differences and spectroscopy: http://lectureonline.cl.msu.edu/~mmp/kap29/Bohr/app.htm as of Dec 7th 2006). The students are working through the tutorial questions that come with the simulation, and are currently dealing with Question 2 ("How will the wavelength of the emitted photon, as the electron returns to the ground state, compare with the wavelength of the absorbed photon, which originally excited the electron into the 5th orbit?").

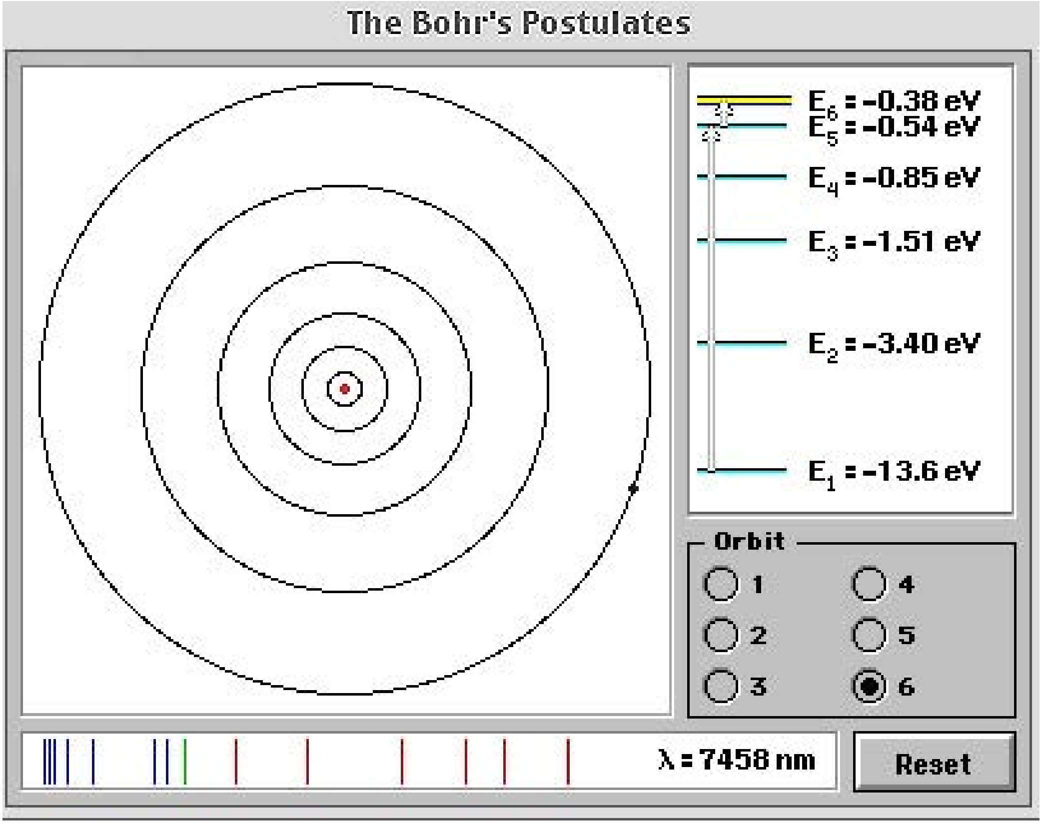

Figure 1. A screen dump of the Bohr model simulation. At the top left is the orbital diagram, centre right is the energy level diagram and at the bottom is the spectral line diagram (in terms of wavelength). By (mouse) clicking on the orbit numbers, the electron can be transferred between the orbits, and the history of transitions is recorded as arrows in the energy level diagram. The last two transitions before the photograph was taken were between energy level 1 and 5 (E1 to E5), followed by E5 to E6. The last one (E5 to E6) is the transition with smallest energy difference and the corresponding spectral line has the longest wavelength (λ=7458 nm shown at the lower right corner), which is flashing (not shown) left of the lower right corner.

In the simulation, the students see a visual presentation of an atom with an electron circulating in one of the orbits. The simulation also provides them with a diagram of the orbits' corresponding energy levels (E1,..., E6), as well as a diagram of the spectrum of the associated light (for the hydrogen atom). The students can initiate transitions between these levels and see to which spectral lines the transitions correspond.

Student (A): [Reading Question 2.] *"How will the wavelength of the emitted photon, as the electron returns to the ground state, compare with the wavelength of the absorbed photon, which originally excited the electron to the 5th orbit?" What?!?* [Puzzlement.]
Student (B): [Having read Question 2 silently again.] *I don't understand this.*
Student (A): *Okaaay…. I understand. We first have to take it to the 5th orbital, and then return to the ground state, comparing the wavelengths.* [They move the electron from the ground state (E1) to the 5th orbit (E5).]
Student (B): *So, now we take it back to the ground state.* [They do E5 to E1.] *There's no change!* [looking at the wavelength (λ) value shown on the spectral line diagram]
Student (A): *Is it? Do it again.* [Sounds doubtful.]
Student (B): [Repeats transitions.] *There's no change.*
Student (A): *Okay, there's no change. Now go to ground* [state].

Here, the students merely look at the values shown on the spectral line diagram, and note that they are identical. They then write down their answer, with no discussion about why it is that the wavelengths of the absorbed photon and the emitted photon are identical. They proceed to Question 3 ("Which electron transition will emit the longest wavelength photon?"), which they tackled in a similarly perfunctory fashion. The only issue they ended up discussing was how much time they had left to complete the simulation tasks, and an assignment due later in the day.

They continue:
Student (A): *Okay, on to question 3.*
Student (B): *We've done question 3. This* [Student (B) points to text.] *this they just tell you. Now, let's go down….*

Here the students are omitting a critical part of the text in Question 3 concerning how to judge the correctness of their answer by checking that they had produced the appropriate wavelength (in this case the line on the extreme right of the given spectrum in the spectral line diagram). Nevertheless, the students press on to complete the task. The focus of the students throughout the simulation seems to be complying with instruction and mainly concerned with getting to an answer, and not on achieving any understanding of the physics phenomena represented in the simulation.

Observing the Presentation

When it comes to the focus *Observing the Presentation,* the simulation is distinctly in the foreground. It differs from having a focus on *Doing the Assignment* in that there is an ambition to understand the simulation in relation to the question. The focus is on the simulation as it presents itself and "how it works". The physics phenomena and situation that the simulation is meant to illustrate and represent are not part of the experience, apart from the simulation being seen as a visual presentation, which can be taken at face value. The relationship to the pedagogical situation is passive, the simulation session is experienced as if it were a demonstration or video that can be watched, possibly explained, and understood.

In the following illustrative extract students are engaged with Question 1 ("Does it take more energy to jump from the ground state to the 2nd orbit or from the ground state to the 3rd orbit?"), at a time when they are still not entirely familiar with the simulation:

Student (A): [Reading Question 1.] *"Does it take more energy for the electron to jump from the ground state to the 2nd orbit or from the ground state to the 3rd orbit?" – Okay, so if you want the electron to move to the 2nd level, it needs energy.*
Student (B): *How do you know that?*
Student (A): [Reading on.] *"In order for the electron to occupy a higher energy state, it must receive energy…". Meaning that if you want to move the electron to the 2nd energy level, it requires energy. Do you understand?*
Student (B): [Peering at the monitor screen.] *What level is it in at the moment?*
Student (A): *It's currently at E3. [Pointing to* E3 on energy level diagram.] *That's E1* [Points.] … *E2* [Points.] … *E3.* [Points.]
Student (B): *Meaning this is E1?* [Points to innermost orbit on orbital diagram.] *Then E2* [Points.] *E3?* [Points.] *Okaaay!* [Aha!]

By the end of the extract, student (B) begins, with the assistance of student (A), to appreciate a relationship between the energy level diagram and the orbit level diagram shown in the simulation.

Manipulating the Parameters

The focus here is on the active use of a simulation to understand the underlying physics phenomenon (or "reality"). Unlike the focus *Observing the Presentation* the student is now the active agent (rather than the passive observer), openly engaged in the learning situation. However, understanding is limited because the phenomenon itself is constituted solely within the parameters given in the simulation.

This focus is for example illustrated by the following extract:
Student (A): [Question] *one: Does it take more energy to jump from the ground state to the second orbit or from the ground state to the third orbit? So if we...*
Student (B): *Just...* [...]
Student (A): *Right, ground state, second orbit, that's 121 nm.*
Student (B): *Yeah.*
Student (A): *And ground state to third orbit it's 102 nm. ehmm. ... If we look up on the little table there* [the energy diagram] *we see that it's much larger difference to the third orbit.*
Student (B): *Yeah.* [...]
Student (A): *Nothing much strange about that I think, I mean, its some sort of gravity-like potential field, it's...*
Student (B): *Exactly.*
Student (A): *It moves to a better potential, worse even.*
Student (B): *Worse, farther away.*
Student (A): *It wants to be close, that's low energy, it's minus lots of electron volts.*
Student (B): *Yeah.*
Student (A): *So.*
Student (B): *Which transition requires the shorter wavelength photon?*
Student (A): *We saw that that was the one to the third layer and from this we can deduce that short wavelength photons are more energetic. ehm. ...*

In the above, the students take their starting point from the first tutorial question ("Does it take more energy to jump from the ground state to the second orbit or from the ground state to the third orbit?"). They start with trying this out in the simulation, and then discuss the results with input from other parts of the simulation (for example "the little table there"). They then find an acceptable explanation for the way the orbits seem to be organized, and draw a conclusion (which is the one mainly intended by the simulation designer). What is shown in the simulation is taken as what is to be learned, and the parameters of the simulation are manipulated (switching between orbits, shifting between space and energy representation), in order to see and explain what happens.

Exploring the Physics

Constituting a focus on Exploring the Physics implies an awareness of the representational nature of the simulation, and of the limits of both the simulation and the phenomenon as tools to understand the world. The simulation is regarded then as no more than a conceptual tool, which can be used to explore and understand the phenomenon.

The following extract from a conversation between two of the students illustrates where they demonstrate a consideration of the physics underlying the simulation:

Student (A): *I wonder, are there more than six states to this, is it some finite limit or have they just chosen that arbitrary, I mean you should...*
Student (B): *I am not sure...*
Student (A): *You should be able to excite it so for example an electron leaves, if you would be ionizing the entire thing in reality?*
Student (B): *But that's not, it doesn't seem to be part of the model* [...] *it must be some simplified model in some way.*
Student (A): *Yeah, ok, what's the next one then. Interesting...* [Reading.]

Student (A) starts to ponder why only six states are shown in the simulation, knowing that there is a particular ionization energy, widening the scope of the discussion from the immediate (tutorial) questions at hand to the Bohr model as a whole. However, this interest wanes quickly and student (A) starts to return to the questions. Student (B) picks up the thread of reflections on issues underlying what is presented in the simulation:

Student (B): *I* [am] *wondering how he* [Bohr] *found out where the orbits are placed. The distances from the centre.*
Student (A): *Shoo.* [Agreeing.]
Student (B): *Some kind of calculation.*
Student (A): *I suppose he used some kind of, it's, what do you call it, a electromagnetic, it is an electro-magnetic figure ... a positive pole and a some negative thing and you can, you should be able to calculate the potential energy required for, then again, there should be, why do you get just those?*
Student (B): *It is kind of interesting how the distance increases* [in the orbital diagram].
Student (A): *It is difficult to dig out from the simulation, I must say.*
Student (B): *Yeah* [...] *but how, how is it possible to figure it out, that is interesting I think, some, hehe, to understand it, how some person, that smart that he can figure out something like this it's different from trying to understand.*
Student (A): *I suppose you could, you must have determined it experimentally, because as you, you can check what photons an hydrogen atom emits and absorbs, and therefore you know the energy states that are possible, you should be able to deduce which length, or radius of rotation you can have.*
Student (B): *Yeah, ok.*
Student (A): *I suppose they did it that way* [...] *hehe let's see the next question.*

The students have initiated a more in depth consideration of the Bohr model, and in so doing have started (possibly inadvertently) to explore the very process of physics knowledge production. However, by the end of the extract, student (A) has turned their attention back towards the more restricted simulation questions at hand.

Table 1. Summary of the delimitations between categories of different focus-of-awareness in terms of the two aspects "view of the nature of physics knowledge" and "view of learning physics".

Focus	Nature of physics knowledge	View of learning physics
Doing the Assignment	Physics is not really present	Fulfilling demands, tasks
Observing the Presentation	Physics phenomenon to be seen and explained	Learning by seeing and someone explaining
Manipulating the Parameters	Physics phenomenon to be controlled, as set by given parameters	Learning by doing yourself and understanding
Exploring the Physics	Ways of seeing, predicting and interpreting phenomenon	Explorative creation of a body of knowledge

Discussion

Analytical exploration of the constitution of the categories

The four focuses we have described above can now be analysed further into what they reflect of, on the one hand, the students' apparent view of physics knowledge and, on the other hand, their apparent view of learning physics. This more clearly delimits the categories from one another. A summary of the analysis is seen in Table 1.

The categorization of the view of learning physics is akin to earlier studies of approaches to learning (Marton & Säljö, 1976; Prosser & Millar, 1989; Säljö, 1979), on a dimension from adopting surface to deep approaches to learning physics. Research on the relation between approaches to learning and the quality of learning outcome indicate a clear correlation (for example Trigwell & Prosser, 1991). Such a relationship seems evident also in the present material and different focuses imply learning outcomes of different nature and scope. We see a focus on *Doing the Assignment* as being essentially non-productive in terms of coming to an understanding of the physics phenomenon under consideration. There are however different degrees of value in the other three focuses.

Common to both *Observing the Presentation* and *Manipulating the Parameters* is that the simulation itself is the main level of interaction; the simulation is taken at "face value" and as a window into "reality", and it fully constitutes the phenomenon. When the focus is on *Observing the Presentation*, the potential learning outcome is restricted in ways similar to what a video or demonstration can "tell" a student, or what the student can glean from it. And whereas the focus on *Manipulating the Parameters* gives the possibility of developing some new understanding, what can be learnt about the phenomenon is still restricted to the (physics) content of the simulation.

The focus on *Exploring the Physics* in some ways sidesteps the other focuses in that here the difference in the view of learning and nature of physics knowledge implies different ways of engaging with the simulation. The view that simulations should and could be taken at face value is not found within this focus. In its place, a quite different epistemological view emerges – namely, that both the simulation and the underlying perceived phenomenon have limitations in their validity and applicability. To constitute a focus on *Exploring the Physics* in a simulation session, it is thus important to have developed a capability of seeing the nature of physics knowledge in that way. Consequently, we believe that the view of the nature of physics knowledge that a student holds is a crucial component in constituting a focus in the simulation situation. And since teachers can play an active role in this process, opportunities can be created for students to broaden their view of the nature of science, which in turn can play an important role in developing a solid physics understanding (Hammer, 1995; Linder, 1992).

Simulations as tools for learning?

Clearly, computer simulations have an important role to play in learning aspects of physics phenomena – most students participating in this study evidently learned about important aspects of the Bohr model and its associated introduction to spectroscopy. For example Steinberg (2000) reaches similar conclusions in discussing his experiences with teaching air resistance to first-year university students. He compares the learning outcomes from simulation tutorials to non-recitation tutorials and finds similar learning outcomes, which would be considered to be better than those from traditional teaching. Of course, we would argue that the claim that simulations are powerful tools for learning presupposes that the simulation has relevant features, that the learning tasks are manageable and seem relevant to the students, and that interventions are mindful and appropriately directed – in short, that the pedagogical context of the simulation shows attributes of "good teaching".

This study has a clear pedagogical orientation, aiming to address pedagogical aspects of using simulations in instruction. This contrasts with the more psychology oriented theme of other recent research on the use of simulations (for example as represented by Ploetzner & Lowe, 2004 and Schnotz & Lowe, 2003). The theme of the Special Issue of Learning and Instruction, edited by Ploetzner and Lowe (2004), is dynamic visualisations and learning, and generally the contributions are occupied with the comparison between static visualisations and dynamic visualisations. The simulations that were used as a basis for the pedagogical situations investigated in this article were dynamic but even though that was important for the students' general attitude and experience, it was not a factor that emerged as crucial for which focus-of-awareness that was constituted and thus the learning outcome. We would argue that this paper calls for a different kind of discussion around physics learning based on using simulations – a discussion addressing pedagogical needs.

Implications for teaching and learning with simulations

What then are the implications of this research for a teacher who employs computer simulations as a teaching and learning tool with students in a university setting? For a start, based on the analysis presented here, we can expect many students (particularly at the first year level) to have as their focus either *Doing the Assignment, Observing the Presentation* or *Manipulating the Parameters*. Seeing that these three focuses represent fairly limited learning possibilities, we believe that the teacher has a vital role to play in assisting students to explore the phenomenon in ways which are not limited to the representation(s) used in the simulation. And in so doing to encourage them to shift towards a form of engagement that has as its focus *Exploring the Physics*. We saw evidence of this taking place as the various interviewers interacted with students, both during the simulation and in conversation thereafter. This supportive role will of course be enacted in different ways as students become more adept at focusing on *Exploring the Physics* during later simulation sessions.

Here are three implications from the results of this article for physics teachers to take into consideration when employing simulations as a tool in teaching and as a support for learning:

- **Recognizing the learning focus** – There are different learning implications for students depending on which focus that they adopt. Thus it is important for the teacher to be attentive to and respond to the students' apparent focus, possibly trying to shift it towards a more fruitful one, especially from focusing on *Doing the Assignment*, or respond appropriately to the implicit expectations with their present focus. The natures of the different focuses indicate how this might be achieved.
- **Mindful interventions** – The space of potential learning outcome is spanned by the students' focuses. For the majority of students, who can be expected to focus on *Observing the Presentation* or on *Manipulating the Parameters*, interventions by the teacher are vital to widen the

space of possible learning outcomes, for example supporting the students to consider things taken for granted or the relation to aspects of the phenomenon not present in the simulation.

- **Epistemological impact** – The ways in which the students conceptualise physics and learning physics impact on their approaches to learning in a simulation session and the outcomes of their learning in such situations.

Finally, we conclude that the passiveness inherent in much traditional undergraduate physics teaching is not necessarily eliminated by the use of interactive simulations. More generally, whatever the tool used to assist learning, it will have limited results if the students' focus of awareness is incongruent with the teacher's goal. However, it is still clear that simulations can be powerful pedagogical tools for bringing central features of a phenomenon into focal awareness for students given a sympathetic pedagogical situation, creating wide possibilities for exploring physics.

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