THE ROLE OF COMPUTER SIMULATIONS IN UNIVERSITY STUDENTS' REASONING ABOUT PHYSICS

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ABSTRACT. The aim of this paper is to describe the different roles that a computer simulation of a physics phenomenon plays in university students' reasoning about physics. In this way, the paper strives to illuminate the potential value of computer simulations as a tool in students' learning, as their reasoning around physics problems implies possible learning outcomes. Four different ways of using the computer simulation were discerned from data collected from students working with a simulation of Bohr's model of the hydrogen atom. The four categories are distinguished by their characteristics of *Answering*, *Implying*, *Interacting* and *Opening*. We describe the categories in more detail, illustrate them from the empirical data and analyze each of them according to an analytical model of learning, with a motive, an act and an object of learning. We also discuss the categories in terms of design of pedagogical settings with simulations.

1. Introduction

Physics education research is a rapidly expanding field of scholarly inquiry and has recently been described as the key to improving student learning in physics (McDermott, 2001). Most physics education research has, over the past three decades, focused on two areas: conceptual understanding and problem-solving performance (for extensive overviews, see Hsu et al., 2004; McDermott & Redish, 1999; Pfundt & Duit, 2000). One of the main findings is that much traditional physics teaching is far less effective in terms of promoting conceptual understanding than many physics teachers appear to have anticipated (Linder & Hillhouse, 1996; Mazur, 1997). There is now a growing consensus among educational researchers that the passiveness of the students in much traditional physics teaching strongly contributes to the poor learning outcomes – teaching by telling is not an effective way of teaching (Redish & Steinberg, 1999; McDermott, 2001). Physics teaching is therefore increasingly drawing on a variety of active learning methods as supplements to traditional teaching.

One such method is to use computer simulations. A survey of recent literature on the subject of computer simulations for educational purposes in the domain of physics and physics-related engineering gives three major groups of report. Firstly, there are papers that report specific and largely non-theoretical usage of simulations in teaching, describing the use of simulations as aids to teaching and learning of specific phenomena (e.g., Kuan & San, 2003; Lee, 2001; Tobochnik et al., 2005). Secondly, there are research studies, using various approaches, of teaching interventions (e.g., Bodemer et al., 2005; Clark & Jorde, 2004; Jimoyiannis & Komis, 2001; de Jong et al., 1999; Pol, 2005; Rieber, 2004; Steinberg, 2000; Yeo et al., 2004; Zacharias & Anderson, 2003). Thirdly, there is a more technical literature on design concerns, often with theoretical perspectives drawn from cognitive psychology and the human-computer interaction community (e.g., Ainsworth, 1999; Ainsworth & van Labeke, 2004; Cheng, 1999). There has, however, been very little research which problematizes teaching and learning with computer simulations from the students' perspective.

2. Analytical framework

Our interest in this study is to capture and describe the ways in which students experience the use of a computer simulation in a pedagogical situation where there is an intention for them to come to a conceptual understanding of certain physics phenomena (here: in the Bohr model). We can thus characterize the study as in Figure 1.

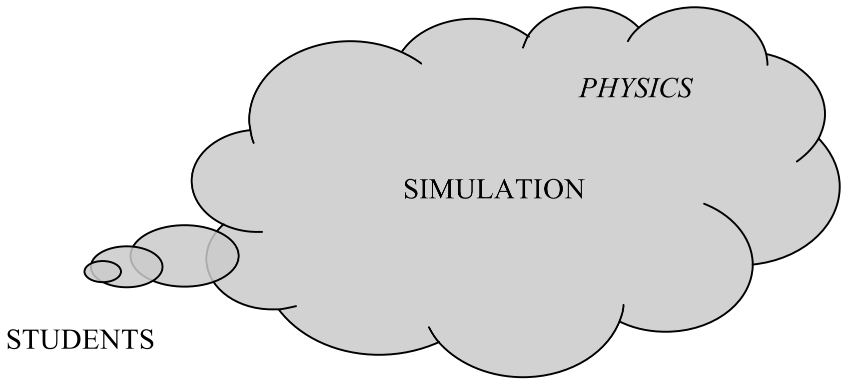

Figure 1. The focus of this study is on how students see, or experience, the use of a simulation against a background of the physics phenomena (here: in the Bohr model) and the pedagogical situation in general, illustrated with a cloud.

While the present study is delimited to focus on the relationship between the students and the simulation aspect of the pedagogical situation, against a background of the specific physics phenomena and the pedagogical situation in general, other relations could have been studied. In particular, the "understanding" of the physics phenomena, the relation between the students and the physics phenomena, could have been focused on, disregarding the simulation apart from its function as a tool for bringing the students experience of physics phenomena to the fore. Further, in the whole research program of which the present study is one part, other relationships have been focused on. We have looked at the relationship between the students and the pedagogical situation in general, encompassing both the simulation and the physics phenomena (Ingerman et al., submitted for publication), and also the process of relating to the physics phenomena, using a simulation to come to a conceptual understanding, against a background of the pedagogical situation (Ingerman et al., in progress).

The research approach we have employed in the study is *phenomenographic* (Marton, 1981; Marton & Booth, 1997), focusing on the qualitative variation in ways students make use of the simulation in the situation. The result of a phenomenographic study is an outcome space of categories of description, where each category can be clearly delimited from its fellows, and where change in some feature of the categories can be traced from one to the next. The outcome space is derived through analysis of a collection of expressions that people offer, fragments of a whole collective of understanding, and it has the character of a hierarchy where categories are successively more elaborate and well-connected.

To express this more concretely, data has been collected here through conversations while pairs of students worked on the simulation. The data thus collected is characterized as a "pool of meaning" – here is to be found all the informants have said in expressing their use of the simulation and their reasoning about the physics. The researcher's task is to find meaning in another sense – as an outcome space that describes the whole of the collected meaning. The researcher strives to understand the phenomenon through the experience of the students, by interpreting the extracts of relevance in the pool against different contexts: Now the context of the actual situation, now the context of what other students said.

There emerges a set of categories where certain features are seen to be critical. The categories are refined successively until the researcher is satisfied that the pool of meaning is exhausted, the categories are distinct from one another, the critical differences are seen clearly, and that there is a progression of complexity, completeness and connectedness. As Booth expresses it: "the set of categories arrived at can be considered to be satisfactory when an internal logical relationship, a hierarchy, is seen to exist between them, which in turn can be related to other descriptions of the phenomenon in question" (Booth, 1997). Then the outcome space can be turned on the overriding research question or the practical issue of improving the conditions for learning.

From a phenomenographic perspective, learning means becoming more able to see greater complexity of aspects in a phenomenon and more connectedness between the aspects, as well as seeing the outline of the phenomenon against the variation of contexts it might be met in. Learning is more strongly associated with an approach that seeks meaning in a phenomenon in a context rather than one that aims to reproduce given facts or to satisfy the immediate demands of the situation. It is seen, then, that learning is more clearly signaled the further through the outcome space we move.

A simulation of the kind used in the study is potentially a very powerful tool for such learning in that it offers several interacting aspects of the phenomenon of the Bohr model of the atom for students to work with, and the visualizations bring the connectedness into view. However, the situation created by the resources around the students is equally important, and the questions posed in the textbook tutorial provide a powerful draw to halt after finding answers rather than seeking the meaning that the answers signify.

The essential act of learning involves becoming aware of some feature or aspect of a phenomenon that was previously taken as given, seeing the potential for a variation where previously there was none. This is tantamount to spying a new dimension to the phenomenon, which we call a dimension of variation. Again, this simulation can be a powerful tool for learning since it offers the user the chance to vary parameters, to see how varying one feature of the model affects another feature, questioning the range of values that are available and so on.

The first and primary constituent of learning is the *outcome* of learning – *what* is learned, what is now seen in a phenomenon or situation that was previous not seen; for learning is an intentional act and always has to be directed at something. A second constituent is the *act* of learning that is undertaken in the situation – *how* the learning is undertaken with the tools to hand (here: a computer simulation); for learning of the sort under consideration is not seen as being ubiquitous or serendipitous. Thirdly, learning has a driving force, or *motive*, which can be derived from the learner's history of learning but is more usefully related to the immediate perceptions of the *demands* of the situation, its relevance structure. These are taken to be the fundamental constituents of an analytical description of learning, and can be illustrated as in Figure 2.

As mentioned earlier, the focus of this study is on the relationship between the students and the simulation, or the different ways in which the students are using the simulation against a background of the physics phenomena and the general situation. So we are focusing on the *act* of learning, but this can be linked to different *potential* learning outcomes and motives, and will be described in the discussion section.

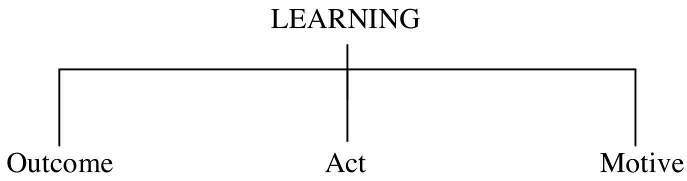

Figure 2. The analytical structure of learning, with an outcome, an act and a motive of learning

3. Method

The study involved first-year university students in physics, drawn both from a Swedish and a South African university. Sixteen volunteer students participated in the study (of which eight contribute directly to the study). The students worked in pairs with a simulation of Bohr's model of the hydrogen atom, taken from *ActivPhysics* by van Heuvelen and D'Alessandris (1999). This simulation was chosen because we judged it to be pedagogically promising, with its multiple representations of the Bohr model, its simplicity and ease of use, its structure as a learning sequence, and its use of complementary visuals and text. The simulation consists of three linked representations (see Figure 3):

1. a diagram of the *electron orbits* (top left), with an electron moving around the proton in one of the orbits (only six orbits are represented);
2. a diagram of the corresponding *energy levels* (top right), with the energy of each level indicated in electron volts (eV); and
3. a diagram of the *spectral lines* that result from the electron transitions (bottom left), with the wavelength of the corresponding photon, indicated in nanometers (nm), and its color[1].

The simulation allows the user to move the electron between the orbits (top left) by clicking on the orbital or quantum numbers (middle right). The transition is indicated in the energy level diagram (top left) by an arrow. The corresponding line in the spectral line diagram (bottom left), with its true colour, starts blinking.

As a way to get the students started and direct their awareness to the intended object of learning, the simulation is accompanied by six tutorial questions (see the Appendix). The questions are mainly conceptual and centred around the *inverse* relationship between energy and wavelength. The students were asked to take their time to explore the simulation with the tutorial questions as a guide and to discuss with one another what they were trying to do. The researcher appeared a few times during the session, to clear up possible problems and queries, and to support the students' discussion of physics. After the simulation session, the students were interviewed about their answers to the questions and how they arrived at them. The simulation session and the interview, which took about one hour in total, was audio taped (after verbal consent) and transcribed soon after the event.

The data in the form of transcripts, backed up by video-recordings, have been analysed to find qualitative differences in the ways the students were perceived to use the simulation. This involves a reading and rereading of the transcript, as described earlier, striving to reach an understanding of the ways the interviewees were experiencing the simulation, in terms of distinct and sparse categories rather than in broad and personalised terms.

[1] It should be noted that all scales in the simulation are non-linear.

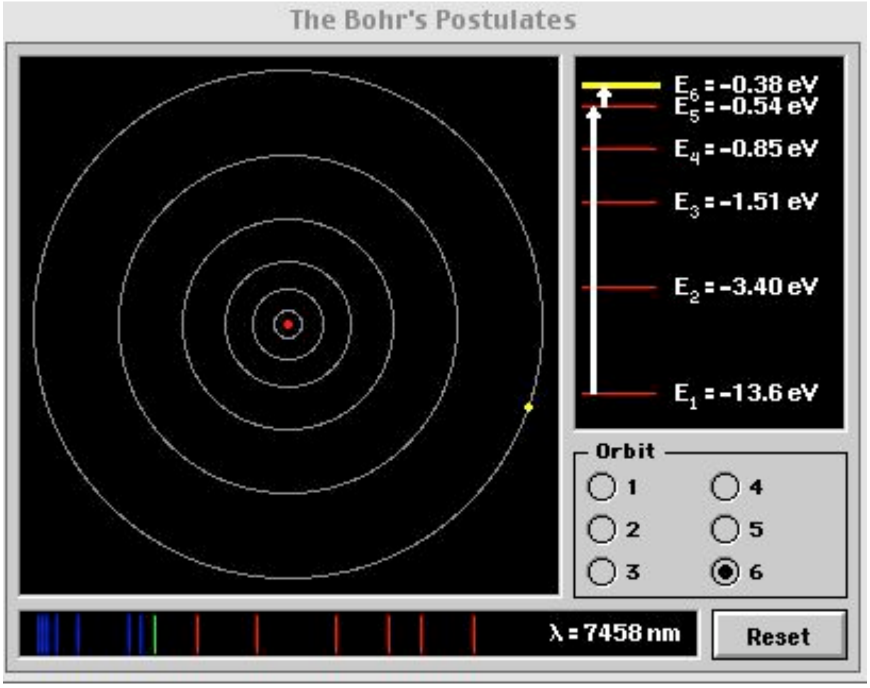

Figure 3. A screen shot of the simulation of the Bohr model of the hydrogen atom. The simulation allows the user to move the electron between the orbits (top left) by clicking on the orbital or quantum numbers (middle right). The transition is indicated in the energy level diagram (top right) by an arrow. The corresponding line in the spectral line diagram (bottom left), with its true colour, starts blinking. In this screen shot, the electron has first been excited to the fifth orbital and then to the sixth orbital, indicated with two separate arrows in the energy level diagram. The last transition, from the fifth to the sixth orbital produced a spectral line with the wavelength 7458 nanometres (nm), indicated to the right of the spectral line diagram.

4. Results

An analysis of the transcripts resulted in four different categories describing the qualitatively different roles of the computer simulation:

A. *Answering*: The simulation is used to answer given physics questions in a simplified and disconnected manner.
B. *Implying*: The simulation is used to extract physics principles that are implied by it.
C. *Interacting:* The simulation is used iteratively and in conjunction with knowledge of physics as support for reasoning.
D. *Opening:* The simulation is used to open up for pondering on physics phenomena.

What follows is a more detailed description of these four categories with extracts from the transcripts to illustrate essential attributes of the categories.

4.1. Answering

In this category, the simulation is used to answer the tutorial questions in a simplified and disconnected manner. The focus is on the medium, the physics deliverables and features of the simulation. The students are just collecting isolated facts or observations, for example in separate representations of the simulation[2]. There is a strong sense of duty to just get the answer to the tutorial question.

[2] It should be pointed out that it is possible to extract principles from single representations, such as the relative spacing in the orbital diagram and the energy level diagram.

For example, in the excerpt below, the students are working with 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? Given your answer, which transition requires a shorter wavelength photon?"

S1 The second one [to the 3rd orbit].
S2 There [from ground state to 2nd orbit] we have a difference of approximately 10 electron volts [looking at the energy level diagram].
S1 Yes.
S2 And from the ground state to the third orbit, there the difference is about 12 electron volts [looking at the energy level diagram again]. If we now look at the wavelengths then … [clicking] … it is 121 nanometers [ground state to the 2nd orbit] … and … [clicking] … 102 nanometers [ground state to the 3rd orbit] ... and this means that *the transition between one and three requires the shortest wavelength*.
S1 Yes.
S2 Observe the two transitions … [Reading the question]… return the electron to the ground state, press reset. Yes.
S1 Yes.
S2 That we have done.
S1 Question 2.

Here, the students first answer the first part of the question (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?) by looking at the energy difference between the ground state and the 2nd and 3rd Bohr orbit, respectively. They then answer the second part of the question (Given your answer, which transition requires a shorter wavelength photon?) by finding the wavelength of the photon that corresponds to the electron transition between the ground state and the 2nd and 3rd Bohr orbit, respectively. But they do not make a connection between these two parts of the question, between energy and wavelength, or between the information they obtained from *different representations in the simulation* (in contrast to the next category). They answer the question in parts, in *separate* and single representations, and then quickly move on. This contained or limited answering of a set question can be linked to a taken-for-granted sense of duty to complete the question implied by the pedagogical situation.

As another illustration of this category, consider the following excerpt, where two students are working 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?"

S1 Ok, just press five on ... [clicking] … and there it blinks [the spectral line].
S2 Yes, 95 nanometers.
S1 Yes, how will the wavelength … [Reading the question again]. Ok, what does the question ask? Ha-ha.
S2 How will the … [Reading the question a third time] … Ha-ha.
S1 I think we should compare the emission … the absorption and emission.
S2 Yes.
S1 And the wavelength between them. Ha-ha … I hope so anyway.
S2 The question says so.
S1 Let us say that.
S2 We return it to the ground state and … [clicking] …
S1 Yeah, and there it is 95 nanometers.

Here, the students only focus on one kind of representation of the photon, its wavelength, and not its energy. Again, they do not make a connection between the information obtained from the energy level diagram (i.e. the energy of the photon) and the spectral line diagram (i.e. the wavelength of the photon), and therefore fail to address this question as an illustration of a fundamental principle: energy conservation.

This missing link between wavelength and energy may be the root of their puzzlement over the formulation of the question. But even if they find it difficult to make sense of the question, they do not try to look outside it, to change representation and try to understand the question in that context.

4.2. Implying

In this category, the simulation is used to "draw out" key physics principles implied by it. The focus is now on the message of the medium rather than the medium. The main difference from the previous category is that, there the simulation is delivering disconnected answers, but here the students are integrating observations, for example from different representations, into key principles. The use of the simulation is, however, not characterized by inquiry but rather by "induction on scanty grounds" and there is no attempt by the students to link what they observe to their prior physics knowledge. In this way, there is still a sense of duty to complete the task and the simulation still takes on the dominant role as a resource in their reasoning.

For example, in the following excerpt, two students are working with 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? Given your answer, which transition requires a shorter wavelength photon?"

S3 Right, ground state to the second orbit is … [clicking] … 121 nanometers.
S4 Yeah.
S3 And ground state to the third orbit is … [clicking] … 102 nanometers. If we look at the little table here [the energy level diagram] we see that it is a much larger difference [in energy] to the third orbit.
S4 Which transition requires the shorter wavelength photon?
S3 We saw that it was the one to the third orbit, *and from that we can deduce that short wavelength photons are more energetic.*
S4 Ok, should we move on to the next question?
S3 I suppose we do.
S4 It is *not too much to say about that.*
S3 No.

Here, the students first find the wavelength of the photon that corresponds to the electron transition from the ground state to the 2nd and 3rd Bohr orbit, respectively (the second part of the question). They then look at the energy difference between the ground state and the 2nd and 3rd Bohr orbit, respectively (the first part of the question). In their answer to the second part of the question, the students are now (in contrast to the previous category) *integrating* the information that is obtained from two different representations in the simulation into a key principle between energy and wavelength: "short wavelength photons are more energetic".

The students do not, however, use their knowledge of physics to predict (as was indicated by the question) or reflect on this observation (that a *big* energy difference corresponds to a *small* wavelength) – they are not *bringing* anything to simulation, they are only putting together two observations in two different representations. And there is still a sense of duty to complete the question and to go on to the next question ("it is not too much to say about that"), as in the previous category.

4.3. Interacting

In this category, the computer simulation is used iteratively and in conjunction with physics knowledge. The focus is on physics *reasoning* as mediated or framed by the simulation and tutorial questions. In sharp contrast to the two previous categories, the students now start to draw on their prior understanding of physics to make predictions and/or to explain what they observe. In this sense, they are now actively addressing the tutorial questions.

For example, in the excerpt below, the students are working with Question 3: "Which electron transition will emit the longest wavelength photon?"

S4 We could just try…
S3 Looking at the graph [the energy level diagram] you can see that it should be the top states, so to speak, it is [zero point] thirty eight and then it goes down to [zero point] five, very few electron volts, about [zero point] one or two, and that is the smallest [difference] there is.
S4 Yeah…
S3 And that should be the one with the *longest* wavelength [photon], because that is the *least* energetic, so to speak.
S4 Exactly.
S3 And we get … [checking out] … 7 458 nanometres compared to, say [level] two to one, which is 121 nanometres.

Here, the discussion moves from one representation (energy) to another (wavelength) with prior knowledge of physics as a link between these: S3 first uses the energy level diagram to identify the *smallest* possible energy transition (the one between the two "top states" or energy levels), then prior knowledge of the *inverse* relationship between energy and wavelength to single out this transition as the one with the *longest* wavelength, and then finally the simulation again to confirm this prediction. This interaction or moving between different representations in the simulation and physics reasoning is the main attribute of this category.

As another illustration of this category, consider the excerpt below, where the students are working with Question 5: "The transition from the 2^{nd} to the 5^{th} energy level required a photon of wavelength 434 nm to be absorbed, which is blue. Adjacent to this blue line in the spectrum of hydrogen is a green line[3]. This line is also due to a transition involving the 2^{nd} level. What other level is involved in the green line transition, the 4^{th} level or the 6^{th} level?"

S3 A photon … 434 nanometers … which is blue. Adjacent to this blue line is a green line … [Reading the question].
S4 Four, five, six … the green line is here between.
S3 I guess that it is two to *six* but …
S4 Hmm …
S3 I mean it [green] is a slightly *longer* wavelength than the one we just had [blue].
S4 Yes, exactly.
S3 So it should involve…
S4 It should be a *longer* jump.
S3 It should be slightly…

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[3] Here we point out a small mistake in the formulation of the tutorial question. The text states that the blue photon is *absorbed* and in the next sentence, it mentions the corresponding *blue* line in the hydrogen spectrum. If the photons are absorbed, they produce an absorption spectrum, which consist of a series of *dark* lines. The colored lines against a black background are due to emission and called a line spectrum.

S4 Things aren't always as we think they should be.
S3 Wait, it's a *long* wavelength. Ahh … let's see what the heck happens. I think I am wrong, come to think of it. It should be two to *four*. [Clicking] Yes, it's the other way around of course.
S4 Do two to four again.
S3 [Clicking] Yeah, that [two to four] should be the green one. Yes, *because we know the formulas and it* [the energy] *is Planck's time the frequency, so it* [the energy] *is inverse to the wavelength, and that means that we won't … to get much energy it is short wavelength*. We are being silly.

Here, the students start by trying to figure out the answer without using the simulation. They know that the green line corresponds to a "slightly *longer* wavelength" than the blue line, and argue that this means "a *longer* jump" than for the blue line. (The truth is the opposite: a longer wavelength corresponds to a *shorter* jump). After a while, one of the students (S1) becomes confused and decides to use the simulation to find out the correct answer: "Ahh … let's see what the heck happens." But at the same time he realizes that they are wrong and the simulation confirms this: "Yes, it is the other way around of course".

Having found the green line, they then continue to confirm or explain its position (two to four) by drawing on two fundamental relations: Firstly, that energy is proportional to frequency: "it is Planck's time the frequency"; and secondly, that frequency, in turn, is inverse proportional to wavelength (this is not explicitly mentioned in the excerpt above). This discussion leads to the general conclusion that energy is inverse proportional wavelength: "to get much energy it is short wavelength", and this confirms their observation from the simulation.

4.4. Opening

In this category, the computer simulation is used as a "springboard" for physics reasoning. The focus is on physics reasoning as motivated or inspired by the simulation and tutorial questions. The students now notice and start pondering on certain interesting features of the computer simulation that are not covered in the tutorial questions. Thus, in sharp contrast to the previous categories, the students are now taking the initiative for exploring the simulation and they are moving in their own direction, guided by their physics knowledge and/or everyday experience.

For example, while working with Question 1, S4's attention is suddenly drawn to a feature of the simulation that is not covered in this question: the speed of the electron in different Bohr orbits.

S4 It [the electron] moves quite *slowly* around as well, compared to in the closest [orbit].
S3 No, I suppose that makes sense.
S4 It seems, it seems…
S3 I mean, it should be some *central force motion thing*, I mean…
S4 Yeah.
S3 It is … positive and negative attracts … *the closer the stronger force*, so that's to be expected.

They notice that the electron moves significantly *slower* in a higher orbital, and they try to explain this observation. The explanation they construct includes different components from physics, such as the notion of "central force motion" and "positive and negative attracts", but in the end it seems to be based on phenomenology: closer means stronger and stronger means faster[4].

At the end of the session, these two students try to recapitulate some interesting things that they have noticed in the simulation, and they return to the speed of the electron:

S3 We noticed that its rotation speed … it is correct, it is *very much lower at the edge* than …
S4 Yes.
S3 Than in the centre.
S4 Like *any other circular motion*, like a …
S3 Like it should be …
S4 What is it called that music … that disc, not a CD, but the old one, the big one?
S3 LP.
S4 LP, exactly, when you put your finger … *and it goes around like this on the outside really slowly*.

Here, they now try to explain the observed fact that the electron moves significantly slower in a higher orbital by drawing on everyday experience. They compare the motion of the electron with the motion of a point on an LP record, and argue that a point at the edge of the record moves *slower* than a point nearer to the centre[5].

5. Discussion

The study we have now presented focuses on the different ways in which students make use of a simulation in a pedagogical situation where there is an intention for them to come to a conceptual understanding of Bohr's model of the hydrogen atom. We could have focused on other relations in the model we presented in Figure 1, for example on the ways students relate a simulation to a particular pedagogical situation (Ingerman et al., submitted for publication) or the process of grasping conceptual understanding that ensues when students work with the simulation (Ingerman et al., in progress). Such studies are indeed associated with the present study and so will not be taken up further here.

Four qualitatively different ways of using the computer simulation were discerned from data. The categories are distinguished by their characteristics of *Answering*, *Implying*, *Interacting* and *Opening*. Here we will first turn our attention to an analysis of the categories according to the analytical model of learning that was introduced earlier in this paper, with a motive, an act and an object of learning. We then consider the implications for instructional design involving the use of computer simulations.

5.1. Further analysis of the categories

The *learning act* in the categories can be linked to different *potential learning outcomes* (see Table 1). Responding to questions in single and distinct representations, as in the category we have called *Answering*, can hardly have more far-reaching learning outcomes than knowing isolated facts. The students are just collecting isolated observations without making meaning from them, taking them as given by the authority of the simulation[6].

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[4] We will return to this quote and the following one in the discussion section and give a more detailed analysis.
[5] The truth is the opposite: the angular velocity is constant, so a point at the edge moves faster.
[6] A similar interaction between students and computer simulations was found by Yeo et al. (2004). They report that the "students appeared to interact superficially with the program's content. They worked rapidly, settling into a pattern of action/response which seemed almost automatic, carried out as if to complete a task rather than to learn from it."

Seeing what is implied but not explicitly stated as a result of the simulation, as in *Implying*, may lead to an experimental and concrete understanding of key principles by extracting them from observations in different representations. The students are now starting to construct meaning by integrating facts or data from the simulation into patterns or principles. There is, however, no reflection on the result, no "looking back" as Polya (1957) would have put it. The students are still in an answer-getting mode. Another learning outcome, in the procedural domain, that may result from this way of interacting with the computer simulation is inductive reasoning or arguing from observations.

Reasoning in interaction with the simulation, as in *Interacting*, may lead to a deeper and more formal understanding of principles through a process of making conjectures or guessing what the outcome of an event will be (predicting), observing what happens, and then deriving the underlying principle from theory (explaining). The students are now actively constructing meaning by looking for the underlying reasons for the patterns or the principles that they draw out from the simulation – they are *connecting* principles to *prior knowledge* of physics. This element of "looking back", or explaining, seems to be directly related to making conjectures, and they are both important parts of scientific problem solving (e.g., Polya, 1957). The kind of scientific thinking that can be learnt is abductive reasoning where arguing from theory is both drawn from the observations and related back to them.

Category	Learning Motive	Learning Act	Potential Learning Outcome
Answering	To satisfy *external* demands, *authority*	*Answering* questions *Collecting* observations from single representation	Knowledge of *facts*
Implying	To satisfy *external* demands while paying attention to *internal* demands	*Addressing* problems *Integrating* observations from multiple representations into principles	An *experiential* or concrete understanding of *principles* To construct meaning by *inductive* reasoning
Interacting	To satisfy *internal* demands while paying attention to *external* demands	*Actively addressing* problems by predicting and explaining *Connecting* principles seen in the simulation to previous knowledge of physics	A more *formal* or abstract understanding of *principles* To construct meaning by *abductive* reasoning
Opening	To satisfy *internal* demands, *autonomy*	*Asking genuine* questions by noticing and exploring *Connecting* principles seen in the simulation to previous knowledge of physics and phenomenology	Physics principles are integrated into *personal experience* of the world To construct meaning by *analogical* reasoning

Table 1. The Interaction Space for a computer simulation of physics phenomena, where the four qualitatively different ways of interacting with the computer simulation are characterized according to three dimensions of learning: the motive, the act and the potential outcome of learning.

Opening up for new issues to ponder, as in *Opening*, may lead to a broader and more personal understanding of principles since the students are taking the initiative to explore something that they find interesting (noticing) by connecting it not only to prior knowledge of physics but also to everyday experiences. The kind of scientific thinking that can be learnt in this category is analogical reasoning, or seeing things from different perspectives.

We want to point out three interesting features of the outcome space described in Table 1. Firstly, as we move from *Answering* to *Opening*, more and more aspects of the phenomenon, the Bohr model, are brought into focal awareness and being connected in the act of learning. This process of making connections ranges from just drawing on a single representation in the simulation (*Answering*) to drawing on multiple representations (*Implying*), from drawing only on the information available from the simulation (*Implying*) to also bringing in prior physics knowledge (*Interacting*) and then everyday experience (*Opening*). It is seen, then, that the students become more and more active and take more and more responsibility for their own learning the further through the outcome space we move, and thus the potential for learning increases.

Secondly, there is an important dividing line between *Answering* and *Implying*, on the one hand, and *Interacting* and *Opening*, on the other. In the first two categories there is a focus on physics as a *body of knowledge*, i.e. *products*, such as facts and principles, while in the last two categories the focus has shifted to physics as a *way of thinking*, i.e. *processes*, such as predicting/explaining and noticing/exploring. More specifically, in *Answering*, the students are focusing on the *medium*, the features and deliverables of the simulation, while in *Implying* they are focusing on the *message* of the medium, the principles that are implied by the simulation. In *Interacting*, the students are focusing on physics reasoning as *mediated* or framed by the simulation, while in *Opening*, they are focusing on physics reasoning as *motivated* or inspired by the simulation. A reading of the complete transcripts shows that it was only when the students went from using the simulation as in *Implying* to *Interacting*, that they stopped making the same mistake about the inverse relationship between energy and wavelength over and over again.

Thirdly, in the first three categories there is an element of *closure* when the students reach their answer to the tutorial question, while the last category is characterized by an element of opening up as the students notice interesting aspects of the simulation, start to ask questions and explore them by trying out different ideas. They are “messing about”, as Hawkins (2002) would have put it. Often, the students are not able to reach or agree on a conclusion and may thus leave the session with a set of genuine questions – and not only answers – which we believe is an important function of teaching.

We can see the outcome space, depicted in Table 2, as an *interaction space* for a computer simulation of physics phenomena, where the four qualitatively distinct ways of interacting with the simulation can be characterized according not only to the act of using the simulation but also to the possible learning outcomes that can result from those interactions. Thus the observable and analyzable space represented by the table of categories can be turned to illuminate the fundamental features of creating and maintaining a productive pedagogical environment where simulations are involved.

5.2. Implications for instructional design

We now turn our attention to the pedagogical situation the students in our study were in, and see in what respects it could be handled differently. We will attempt to bring out the learning possibilities offered to the students in relation to elements of the context, and describe them in terms of the structure of the categories. We are working towards developing insights into the implications of the results for learning situations involving simulations. The discussion will centre on the features of the analysis as they relate to the pedagogical situation.

5.2.1 The pedagogical setting

Let us recapitulate briefly on the pedagogical situation underpinning our study. One prospect was to trial a tutorial based on a computer simulation of the Bohr model of the hydrogen atom, taken from *ActivPhysics*. The present simulation was chosen because we judged it to be pedagogically promising, with its multiple representations of the model, its simplicity and ease of use, its structure as a learning sequence, and its use of complementary visuals and text. The researcher framed the simulation and the accompanying tutorial questions with instructions to the students to take their time to explore the simulation, to discuss with one another what they were trying to do, and to be prepared to discuss the Bohr model as well as how they addressed the tutorial questions after the session. The researcher appeared a few times during the simulation session, to clear up possible problems and queries, and to support the students' discussion of physics as well as the questions. After the session there was a longer discussion between the students and the researcher.

5.2.2. Learning goals: product and process

The goals for students using the simulation comprise learning outcomes in terms of both the product of better understanding of the aspects of the Bohr model and how these aspects are related to one another, as well as the process of reasoning around the phenomena of physics. But the tutorial does not explicitly state them and they are thus not explicitly shared with the students[7] (see the Appendix). Neither were these learning outcomes discussed in detail by the researcher when presenting the tutorial.

To judge from the transcribed conversations, it was only very late in the session, if at all, that these learning goals were addressed by most of the students. Instead, the tutorial questions were perceived as having implicit goals of a different kind – as questions to answer for their own sake in a simplistic and disconnected way (as in *Answering*) or to "second-guess" for simple principles (as in *Implying*). The oral instructions given by the researcher to discuss and explore were apparently too weak and unspecific for many students to interpret as goals for learning. In some cases the students saw learning goals in terms of discussion, interaction and pondering (as in *Interacting* and *Opening*), but these more reflective episodes were often cut short, typically by one of the students returning to the perceived task in hand, which focused on finding answers.

Our conclusion is that in order for the simulation to play a significant part in the students' learning – as is possible in *Interacting* and *Opening* – there have to be more explicit and negotiated learning goals that encourage reflection on the aspects of the simulation and the relations between the aspects, and thus allow and support physics reasoning.

5.2.3. Feedback and assessment

Two of the most important and effective ways of communicating and negotiating the learning goal of a pedagogical situation are feedback and assessment. In the present case, three main sources of feedback to the students can be identified: from the simulation as such, from collaboration within the pairs of students, and during the interventions of the researcher. The feedback which the tutorial questions encourage the students to get from the simulation is

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[7] Nowhere in the tutorial is it mentioned that one of the main learning outcomes is to find the relation between energy and wavelength, and in general, explicit product goals are completely lacking. When it comes to process goals, the students are often being asked, in different and perhaps more or less clear ways, to predict the outcome of an event, but they are never asked to discuss and explain the outcome, for example, by being asked why their prediction was correct or not. In this way, clear process goals are also lacking.

clearly centred on getting answers in terms of yes or no, or of quantities (energy, wavelength etc.), rather than the quality of understanding or the associated physics reasoning. In this sense, the simulation encourages the first two categories, *Answering* and *Implying*, reinforcing the perceived implicit simplistic goals discussed above. Feedback which concerns qualities that are at the core of the second pair of categories, *Interacting* and *Opening*, is less frequently supported by the questions but was found, in particular, in the interaction between students and with the researcher, pointing to the importance of a partner in reasoning who is responsive and allows quality of reflection.

5.2.4. Collaboration and physics reasoning

The nature of the collaboration between the students was a key element for the role of the simulation for learning. While a *necessary* condition for a better potential learning outcome was the simulation playing the role of opening up for pondering on physics, it was, however, not a *sufficient* condition. More than once, such an episode was prematurely terminated when the students failed to bring adequate physics knowledge and/or experience into the discussion for it to reach a solid conclusion. That is, when the students took the initiative to explore something that they found interesting (as in *Opening*) they also started to draw on a much wider range of *conceptual resources*, of the kind introduced by Hammer (2000), to explain what they observed[8]. But they were not always able to choose an *appropriate* conceptual resource for the specific situation.

Let us give an example of from the different ways in which a pair of students tried to explain why an electron moves more slowly in a higher orbital, as cited earlier in this paper. The first explanation they constructed for this inverse relationship between speed and distance includes different components from physics, such as the notions of “central force motion” and “positive and negative attract one another”. But in the end the discussion is based on what we can refer to as two *phenomenological primitives*, or p-prims, as those introduced by diSessa (1993): “closer means stronger” and “stronger means faster” – and combining them gives the inverse relationship between speed and distance. In this case, the choice of resource (or dyad of p-prims) is appropriate to the situation since the first p-prim, “closer means stronger”, corresponds to Coulomb’s law, and the second p-prim, “stronger means faster”, corresponds to Newton’s second law.

Later in the session, the students returned to the speed of the electron and tried to construct an additional explanation for the inverse relationship between speed and distance by drawing on a different resource. Now, they compared the motion of the electron with the motion of a point on an LP record. This analogy suggests that the students are now thinking of the orbiting electrons as comprising *a rigid body* (i.e. moving with the same angular velocity) instead of as *individually* orbiting particles (as in the previous explanation). In this case, the choice of resource is not appropriate to the situation since electrons do not move as a rigid body and it would give a *linear* relationship between speed and distance rather than an inverse relationship. That is, an electron would move *faster* in a higher orbital. The students did not, however, notice this conflict since they also (wrongly) argued or recalled that a point at the edge of the record moves *more slowly* than a point nearer to the centre.

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[8] Hammer (2000) describes conceptual resources as “a variety of ways of thinking about the question”, which may include both concepts and contexts. “The important point here is that, as a physicist, you have developed a range of resources for thinking about physical situations. Given a familiar problem, you already know which of these resources to apply, and you do so efficiently. Given an unfamiliar problem, you need to search through your resources, perhaps trying several of them out before you arrive at those you find to be useful. Often […], you have active at the same time multiple ways of thinking about a problem that conflict with each other, and much of the work you need to do is to reconcile that conflict.”

All in all, this example shows two interesting things. First, when the simulation plays the role of opening up for pondering on physics, this is a necessary but not sufficient condition for a better learning outcome. What students might learn from the simulation also depends on what they *bring* to the simulation, what kinds of resources they are drawing on, and if they are able to resolve potential conflicts between them. Secondly, the students found it difficult to explain the inverse relationship between speed and distance for an electron without resorting to *ad hoc* explanations. What we find remarkable is that the students never considered writing down any formulas to derive the speed of the electron as a function of distance, when they might have been encouraged to make use of mathematics in their discussion, thus acting as a powerful complementary conceptual resource for unfamiliar physics problems.

5.2.5. Multiple representations

In the literature, simulations are often advocated as supporting learning, in particular because of the possibility to have multiple representations of a phenomenon simultaneously present to the learner (e.g,, Ainsworth, 1999). This is in full accord with our own view of learning, variation theory (Marton & Booth, 1997; Marton & Tsui, 2004). But this study shows clearly that the presence of multiple representations does not automatically mean that the students integrate them or that they stimulate their interest to learn, as seen in *Answering*.

The occasions when representations are linked to one another can be traced to direct orders in the question being addressed, pointing to the importance of explicit goals; to a query from the other student or the researcher, pointing to the importance of collaboration and feedback; or to an apparently spontaneous noticing of a certain feature of one representation and trying to relate it to a feature in another representation, thus exploring their interrelated meaning.

But, as mentioned earlier, a reading of the complete transcripts shows that it was only when the students also made a connection to their prior knowledge of physics, as in *Interacting*, that they stopped making the same mistake (in particular, concerning the inverse relation between energy and wavelength) over and over again. Thus, for a better potential learning outcome, a connection has to be made between representations as well as between representations and prior knowledge.

6. Conclusions

This study clearly shows that students, when using a computer simulation in a pedagogical setting where there is an intention for them to come to a conceptual understanding of physics phenomena, do not necessarily become active or interact with the simulation as was intended by the researcher and designer. We conclude that several different factors must be aligned for productive learning outcomes. In particular, the way in which the simulation is approached and the students' prior physics knowledge and experiences brought into the situation. It is our role as teachers to help provide the alignment of these factors to students. Our main tools in that trade are:

- to make the learning goals transparent to the students in the pedagogical situation, and try to discourage simplistic approaches to the challenges they pose;
- to formulate the learning goals at least partly in terms of physics reasoning and encourage reflection on genuine queries that arise from tackling the tutorial questions;
- to intervene as teachers to give quality feedback on the student-simulation-physics interaction. It is important to set up the assessment in such a way that it affords interaction and reflection rather than answering and second-guessing.

Finally, it should be borne in mind that the students need to bring their physics knowledge, experience and ways of thinking to the simulation tutorial as well as honing their physics understanding and reasoning by virtue of the simulation.

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Appendix: Bohr simulation tutorial questions

In 1913, Niels Bohr constructed a theoretical model of the hydrogen atom in which the energy of the electron as it orbits the nucleus can take on only certain allowed values. Electron orbits at these allowed values, or energy states, are stable. He assumed that no other energies produced stable electron orbits. He was driven to construct this model by the common knowledge that atoms radiate and absorb only certain allowed values of energy.

The simulation indicates the stable orbits predicted by Bohr's model, along with the electron energy corresponding to each orbit. The electron is currently in the lowest energy state (the most negative), referred to as the ground state. In order for the electron to occupy a higher energy state, it must receive energy from some outside source. Typically, this energy is transmitted to the electron through the absorption of a photon.

Select a higher orbit for the electron and watch the electron absorb the incident photon.

Question 1: Absorption

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? Given your answer, which transition requires a shorter wavelength photon?

Observe the two transitions, paying careful attention to the wavelength of the absorbed photon. To return the electron to the ground state, press Reset.

Once the electron is in the higher energy state, the only way to return to the ground state is through the emission of energy. This energy is typically emitted in the form of an electromagnetic wave; a photon. Excite the electron from the ground state to the 5th orbit by absorbing a photon.

Question 2: Emission

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?

If you know the initial and final energy states of an electron, you can calculate the wavelength of the photon emitted, or absorbed, in the transistion. Conversely, if you know the wavelength of the photon, you should be able to figure out the initial and final energy states.

Question 3: Longest Wavelength

Which electron transistion will emit the longest wavelength photon?

Once you think you know the answer, excite the electron into your predicted initial state and then allow it to decay into your predicted final state. Did you produce the wavelength on the extreme right side of the spectrum? (Although this wavelength is indicated in red, it is, in fact, in the infrared portion of the spectrum.)

An interesting observation is that as the energy of the electron increases, the allowed states for the electron get closer and closer together in energy. At low energy (and small radius), the allowed states are widely spaced in energy, and Bohr's novel hypothesis that only certain, discrete energies are allowed is quite apparent. As the energy (and the radius) increase, the energy spacing between the allowed levels decreases and the electron's allowed states form, almost, a continuum. This progression, from discrete allowed states at very small energy and radius to the continuum of allowed energies predicted by classical mechanics, is a manifestation of what is known as the correspondence principle. The correspondence principle states that in the proper limit, in this case large energy or radius, quantum results (discrete energy levels) must give way to classical results (continuous allowed energies). The correspondence principle served as an important organizing principle in the early days of quantum theory.

Question 4: Predicting Wavelengths

In order to jump up from the 2nd energy level to the 5th energy level, how much energy must the electron absorb? Assuming this energy is transferred to the electron through photon absorbtion, what wavelength photon must be absorbed?

Compare your calculation with the simulation.

Question 5: The Green Line

The transistion from the 2nd to the 5th energy level required a photon of wavelength 434 nm to be absorbed, which is blue. Adjacent to this blue line in the spectrum of hydrogen is a green line. This line is also due to a transistion involving the 2nd level. What other level is involved in the green line transistion, the 4th level or the 6th level?

Question 6: Predicting Transistions

One day while reflecting on the spectrum of hydrogen, you turn your attention to the infrared line at 1875 nm. What electron transistion produces this line?

Once you think you know the answer, excite the electron into your predicted initial state and then allow it to decay into your predicted final state.

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