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The learners' experience of variation
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Following students' threads of learning physics in computer simulation sessions

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Abstract

This article attempts to describe students' process of learning physics using the notion of experiencing variation as the basic mechanism for learning, and thus explores what variation, with respect to a particular object of learning, that students experience in their process of constituting understanding. Theoretically, the analysis relies on analytic tools from the phenomenographic research tradition, and the recent group of studies colloquially known as the variation theory of learning, having the notion of experiencing variation as a key for learning at its core. Empirically, the study relies on video and audio recordings of seven pairs of students interacting in a computer-simulation learning environment featuring Bohr's model of the atom. The data was analysed on a micro-level for the emergence of student-recognised variation, depicted in terms of 'threads of learning'. This was done by linking variation around aspects of the object of learning present in the situation and attended to by the students to new ways of seeing – characterised as an expanding anatomy of awareness, and hence as learning.

The students' threads of learning are characterised in terms of two stages of learning progress: (1) discerning variation, and (2) constituting meaning from this experience of variation (experienced as holistically *relevant* in the students' conceptual domain of physics and the Bohr model). Two groups of threads of learning were identified: one where the variation experienced by students was within an aspect of the object of learning, and one where variation was across several aspects.

Keywords

Experiencing variation; physics education; university education; phenomenography; learning as it happens; Bohr's model of the atom; computer simulation learning environment

Introduction

There has been a recent renewed interest in investigations looking into the process of learning *as it takes place*, particularly in science education. This research attempts to describe mechanisms for learning and the structure of understanding as it develops (for example, Clarke & Collins, 2007; Heywood & Parker, 2001; Lidar et al., 2006; Lindwall & Lymer, in press; Tao & Gunstone, 1999; Wickman, 2004; Wickman & Östman, 2002a, 2002b). Developing this interest is for example important in finding ways of connecting the huge amount of research work done on learning outcomes and conceptual difficulties to the dynamics of learning and teaching practice, and thus informing the crafting of teaching practice.

The purpose of this study is to argue for an approach to investigating the process of learning, that we find particularly powerful to explore the understanding of a particular object of knowledge *as it develops*, where the phenomenographic notion of experiencing variation is the basic mechanism of learning (Marton & Booth, 1997; Marton & Tsui, 2004). This variation is then what is characterized as the experienced variation of critical aspects of the object of learning, leading to seeing new parts of the object of learning and new ways of seeing the object of learning holistically. Thus our overarching research objectives addressed in this study are:

- to develop descriptions of the process of learning making use of the notion of experiencing variation as the basic mechanism for learning; and,
- to explore what variation, with respect to a particular object of learning, that students' experience in the process of constituting understanding.

The strength of our argument comes from the application of our analytic tools, which are anchored in the phenomenographic tradition, in the analysis of a set of extensive and detailed empirical data. The tools principally were variation, object of learning, and ways of seeing. The key difference to previous work is that we bring these tools to bear on empirical data for individuals, as their process of learning unfolds. In that way we stay close to the traditional phenomenographic focus on the learners' perspective, and variation in their experience on the one hand, and make powerful use of tools available in the anatomy of awareness on the other. The data consists of seven hours of video and audio data capturing pairs of physics students interacting in a computer-simulation learning environment focusing on the relationships between light emission as characterized by energy and wavelength, the discrete nature of energy levels, orbital representations, and level transitions contextualised by Bohr's model of the atom.

In the analysis, we identified episodes, critical in terms of variation for the students' learning, and collected them into *threads of learning*, which we have constituted as a kind of generative metaphor (Schön, 1983) to describe the process of learning. Thread is used in the sense of 'continous aspect of a thing' (Oxford dictionary of current English, 8th edition). A thread of learning is recognised in an episode of description and/or action judged within our conceptual framework to be critical for developing an understanding of an aspects of the object of learning or an associated concept.

The phenomenographic tradition and variation as a critical learning construct

In the phenomenographic tradition, the notion of variation is a key concept. Even though the everyday meaning of variation is partly retained, it might be somewhat confusing that the variation that is referred to within the tradition may be with respect to different entities and experienced by different agents. In 'traditional' empirical phenomenography (such as, Marton et al., 1977; Marton et al., 1984), what varies is the ways of experiencing a phenomenon, and this variation is what is captured in categories of description, by the researcher, who is the one experiencing the variation. The variation is then understood as a *qualitative* variation. On the basis of numerous investigations, attention then turned towards theoretical development and exploration of the philosophical underpinnings, and the concept of experiencing variation took a leading role in the theoretical description of learning as an anatomy of awareness (Booth, 1992; Marton & Booth, 1996, 1997) that is set in a structure that was for the most part originally formulated and described by Gurwitsch (1964). The key to learning was seen to depend on the learner experiencing (qualitative) variation. This variation is with respect to the important aspects (of the phenomenon of interest) and leads to the constitution of structure and meaning.

As the discussion continued, a new research focus emerged, concerning what essential variation around critical aspects was offered to the students in a teaching situation: what constitutes the space of learning. Consequently, studies of the space of learning and the learning opportunities it offered (as they are created by the teacher) have been carried out, primarily in secondary school classrooms in various subjects (Physics: Linder et al., 2006; Ling et al., 2006; English, Chinese and Physics: Marton & Morris, 2002; Marton & Tsui, 2004; Tse et al. , 2007; Swedish: Holmqvist et al., 2007; Economics: Pang & Marton, 2003, 2005; Economics in higher education: Rovio-Johansson, 1999; Mathematics: Runesson, 1999). This branch of studies is colloquially known as relying on 'variation theory', often described as 'learning studies' (modelled on the tradition of lesson studies, see Pang & Marton, 2005). Again, the researcher is the one bringing out the variation, which is offered in the teaching situation. The goal is to create new and powerful possibilities for learning. Much of the focus has been on 'enacting' an object of learning with students so that they are exposed to an enhanced potential for experiencing the important variations, and thus the critical aspects of a given object of learning. The researcher may bring out a 'variation in the variation offered', by contrasting and comparing different teachers and teaching occasions.

The approach in this article has a complementary take on variation. The theory of learning and awareness is again taken as a starting point, but now *empirical* attention is turned towards the variation, as attended to by the *learner,* – here, in a pedagogical situation involving a computer simulation about Bohr's model of the atom – and investigating how the variation attended to is related to the constitution of understanding. The essential variation around critical aspects of the phenomenon is again in focus, but it is now as experienced by individual learners, in as much as that experience is accessible through empirical sources.

We see a phenomenon (or the object of learning) as being constituted in the experience of a number of discerned aspects – here predominantly the aspects as defined by, and shared in, the physics community or discipline (including teachers, textbook authors, and simulation designers) that are accepted to be the features that carry meaning. This is neither to say that the students are aware of the phenomenon in all its aspects, nor that they have a full understanding of a particular aspect. Then the process of learning can, theoretically, be described as coming to discern an aspect within the whole and relating it to other aspects, thus lending greater cohesion and detail to the phenomenon as a whole. A representation, as we use the term, is a model that presents a phenomenon, situation or construct (or parts of them) in a particular way, namely by bringing certain aspects of the phenomenon, situation or construct to the fore while allowing other aspects to recede into the background. A simulation is capable of separating aspects of a phenomenon that are in reality, and in models, inextricably intertwined, and this separation may support the experience of variation.

Study setup and pedagogical setting

Our data collection was informed by our interest in looking into the process of learning as constituting understanding vis-à-vis the mechanism of experiencing variation with respect to aspects of an object of learning. Being involved in a project that sought to introduce physics-learning computer simulations that were designed by drawing extensively on representation research (van Heuvelen, 1991) we recognised that using simulations would provide us with an ideal interactive learning setting to situate our study in. We chose a simulation where we judged that the potential for facilitating learning was good. On the overall level, this choice was based on our experience as physics teachers, but we also recognised potential from a more theoretical point of view: In the presence of several different representations in the simulation we saw interesting variation possibilities – in terms of opportunities to attend to variation – around important aspects of the phenomenon. This simulation concerned photon energy as it related to emission wavelength and frequency, in the context of discrete energy levels, orbital representation and level transitions. The simulation came from van Heuvelen and D'Alessandris (1999).

From the point of view of teaching physics, we argue that the most powerful way of understanding atoms in terms of their emission properties is through what is encompassed by the Bohr model (or expressed by the Bohr postulates). This is then the *intended* object of learning – what we as teachers aim that the students should learn in a pedagogical situation where they interact with this simulation. The Bohr model of the atom is a quantitatively good model for describing the spectrum of emission associated with the hydrogen atom, and is limited to qualitative arguments for other atoms. By assuming that the single electron can only have certain specific energy levels, one at a time, it is possible to explain the discrete spectrum of light (with respect to its wavelengths) emitted from (or absorbed by) the atom. When an electron moves or 'jumps' between two energy levels, the energy difference is inversely proportional to the wavelength of the emitted (or absorbed) light photon. Usually the Bohr model is associated with the planetary model of the atom, in which a nucleus is surrounded by a number of possible electron 'orbits'. The simulation used (including its accompanying questions) particularly emphasizes the relationship between the wavelength of a photon and the energy difference of the associated energy transition.

We saw the learning potential with the simulation primarily in terms of: the simulation's multiple portrayals of the different aspects of Bohr's model; its ease of use and simplicity; its setup as a *learning sequence*; its structure of complementary visuals and text that supported students working in pairs and discussing the meaning of and relationship between different aspects; and, its realm of visualisation from modelling to manipulation. A screen dump of the simulation is shown in Figure 1.

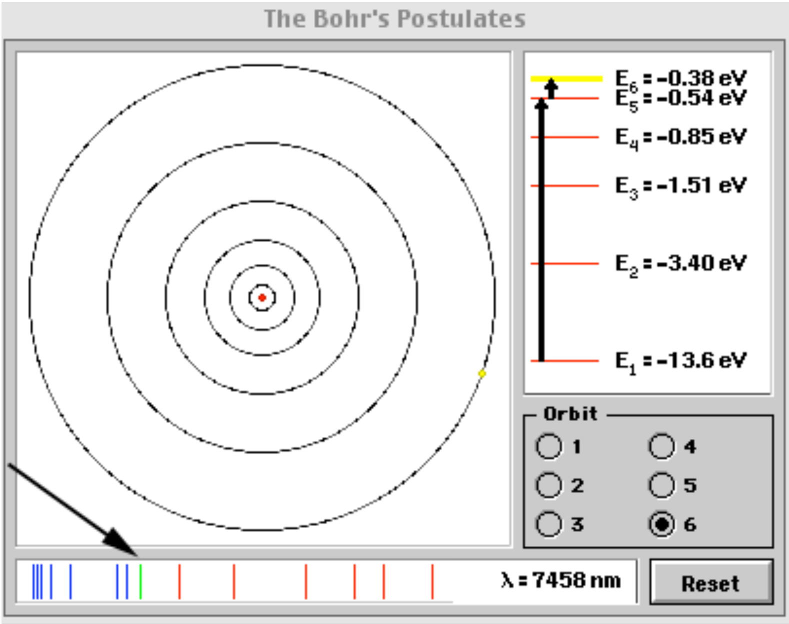

Figure 1. *A 'screen dump' of the Bohr model-simulation is shown. At the top left is the orbital diagram, at the top right is the energy level diagram and at the bottom is the spectral line diagram (in terms of wavelength). By (mouse)clicking at the orbit numbers, the electron can be transferred between the orbits, and the history of transitions is recorded as arrows in the energy level diagram. The last transition before the screen dump was taken, was between energy level 5 (E5) and E6, being the transition with smallest energy difference (0.16 eV) and the corresponding spectral line with the longest wavelength (λ=7458 nm shown at lower right corner) is flashing (not shown) rightmost in the scale. On the left hand bottom an arrow has been added to the picture indicating the 'green line' in the spectral diagram (the seventh line from the right). The colour of light associated with this spectral line is green, lines to the left are blue, while lines to the right are red.*

The simulation used consists of three representations, each offering the potential of experiencing variation in critical aspects of Bohr's model. All of these are given on the computer screen simultaneously. They are an orbital system, an energy-level diagram and a diagram showing the spectral pattern that corresponds to the energy transitions between orbital energy levels (see Figure 1). The simulation allows a user to move the electron between orbits/energy levels, observe the corresponding energy absorbed or emitted on the energy-level diagram and the relevant emission (spectral line) as a function of wavelength (labelled λ in Figure 1).

Representation in simulation	**Defined Aspects**		
	Number of levels	Discreteness	Spacing
Energy level diagram	6	Yes	Increasing
Spectral pattern	15	Yes	No obvious pattern
Orbital diagram	6	Yes	Decreasing

Table 1: *The relation between three aspects of the Bohr model and the three representations in the simulation.*

Table 1 makes explicit three aspects of the Bohr model and how they relate to the three representations in the simulation and the potential variation inherent in the representations, seen one by one and together. For example: the number of levels varies between the representations, but also compared to other experienced (or imagined) possible choices; the discrete spectrum contrasts and varies compared to a continuous spectrum (all energies allowed); the spacing in the different representations, have patterns that are apparent and contrast to each other, as well as to other possible patterns (such as, all distances the same); and, there is also variation within each representation – for instance, the distances between the levels varies.

A number of tutorial-type questions accompany the simulation. These aim at complementing the simulation by directing the users' attention to central parts of the intended object of learning as part of taking the user through the simulation in a systematic way.

Data collection and analysis

One of the challenges we faced when collecting the data was how to capture data that reflected and could be analysed in terms of the students' learning-in-action. In order to encourage students to be as articulate as possible about what they attended to in the simulation (and the associated physics) we decided on the following strategy:

The data collection would be set up as tutorial sessions, using the setup of the simulation and its additional questions. Students from a class that had recently studied the Bohr model of the atom were recruited for the study. They were asked to regard the sessions as trials for tutorials possibly to be included in the course the coming year, and as an extra opportunity for them to learn more about light emission from Bohr's model of the atom. After an introduction, the students were to work with the simulation guided by the accompanying questions, and then engage with a researcher in a discussion around Bohr's model, the simulation and their experience. The main point of following the students when they were progressing through the simulation sequence was to try to capture how they interacted with different aspects of the simulation and what aspects of the learning task and the Bohr physics they attended to (primarily as seen in their actions controlling the computer simulation and in their conversation). The post-discussion served on the one hand to provide further meaning to the students' actions, discussions and to the understanding they might have constituted, and on the other hand it was a possibility to facilitate further learning about the Bohr physics.

Students worked *in pairs* with the simulation and the tutorial questions. One motivation for this was to increase the amount of data around what the students were seeing and doing with the simulation. Another motivation was making use of student cooperation to facilitate each others learning. Thus, they were encouraged to discuss and explain to each other their acts, queries and thoughts.

This setup differs in two important respects from a more clinical experimental setup focusing on students' learning when interacting with a computer simulation: First, that students worked in pairs rather than individually, and second, that the researcher attempted to facilitate the students' learning, taking the role of a teacher within the data collection. This does put the students in a more realistic or naturalistic learning setting, we would argue, while the nature of the learning process stays the same. The grouping of two students will inevitably shape the learning experience, what students attend to, and what variation that is enacted in the interaction with the simulation. The queries, and explanations, from the researcher also serve to direct the students attention to variation enacted with the simulation, and complement the structure and meaning gleaned from the situation.

Since the analysis was carried out in parallel with the whole of the data collection, some elements of the individual sessions varied. In some cases, we interviewed students beforehand about their understanding of the Bohr postulates, partly to make their initial understanding explicit and partly to reveal empirically the aspects of the Bohr model that are educationally critical for understanding it in a 'physicist' way (as a step towards how the students interacted with these critical aspects, which was our overall goal) . In other cases we engaged with the students and their initial impressions immediately after they had acquainted themselves with the simulation. In all cases we asked the students to regard the accompanying questions as a guideline for their exploration, and to expect to discuss the questions in the concluding interview with us.

In total we followed 14 students in seven simulation sessions lasting 40 to 70 minutes. The initial four sessions were situated at University of the Western Cape in South Africa and the remaining three sessions were situated at Chalmers University of Technology in Sweden. The South African students, five women and three men, were first year students not majoring in physics, taking a one-year service physics course. They had already covered Bohr's model of the atom as one topic, and according to their teacher and their test results, the group of participating students included strong, weak and intermediate students. The pairs of students who worked together all knew each other before the sessions. The Swedish students, five men and one woman, were first year students, majoring in physics. Their physics courses at the university so far had not included discussion of the Bohr model, but it had been covered in the Swedish pre-university programme of the upper secondary school at a level of detail similar to the simulation. All of the students could in this context be regarded as strong.

The students' interaction was captured as audio and video data – audio of the conversation, and video both of the computer screen and an overview of the students working. The sessions were transcribed verbatim and comments about the students' interaction, as well as their interaction with the simulation, were added. The language in the session conversations between students and in the interviews was English, which, although it was a second language for all students, was a language used in some or all their classes and literature.

We went about the analysis in an exploratory way, and the essence of analysis shifted and developed. To start with, two of the authors jointly looked for instances of learning, inspired by Booth and Hultén's (2003) search for pivotal contributions to a discussion that opened dimensions of variation. Then we adopted an approach to look for episodes of discussion and interaction where we could judge students seeing or acting differently towards the simulation as a characterization of more complex ways of constituting understanding of the underlying principles of Bohr's model. This procedure was aiming at describing what was in focus for the students, and the variation in how the episodes and thus the understanding were constituted. At this stage, the remaining author, initiated a re-interpretation, and consequently our understanding of the object of analysis evolved, moving towards identifying episodic threads, which could be seen as a sequence of critical episodes characterised as 'threads of learning'. In the empirical material there are threads of learning leading to the students seeing something in a new way, as well as threads ending up in apparent conceptual cul-de-sacs. During this process we continued to collect new data, giving us new perspectives as well as possibilities to ask new questions and develop the analysis further. The three Swedish sessions were simultaneously, but independently analysed for 'threads of learning', by two of the authors. These independently identified threads were in almost all cases very similarly delimited in terms of critical episodes, and the identified variation the students attended to likewise. The structure of the threads in the new material were fully in line with previous results. This was taken as an indication that the analysis was mature; thus we returned to the material as a whole, and more carefully described the details of the results. It is the 'threads of learning' that make up the substance of the results to be presented below, and the ways in which we interpreted them that introduce the following discussion. The collection of 'threads of learning' is to be regarded on one level as a collection of case studies, empirically modelling the process of learning, having been synthesised using a particular theoretical framework (phenomenography and variation theory), and on the other level the threads of learning are a unit of analysis, where qualitative variation can be discerned between different threads, which in turn constitute a pair of categories.

Results

We found it fruitful to describe the development of a capability of seeing something in a new way, in other words, learning, in two main stages.

- Discerning variation with respect to one or several aspects, opening a dimension of variation.
- Recognising meaning of or the essence of this variation, that was experienced as holistically *relevant* in the students' conceptual domain of physics and the Bohr model. The essence might be called structure or pattern, and is what constitutes an aspect of the object of learning and its meaning. An experience of *relevance* in this way has the potential of supporting a more 'stable' way of experiencing the phenomenon, which includes an appreciation of context. In other words the capability to recognise the phenomenon in a way that overarches a number of contexts.

While opening a new dimension of the phenomenon through the experience of variation indicates a different whole of the phenomenon compared to what has previously been discerned, it may not be immediately clear what constitutes the meaning and (the full) structure of this dimension, in relation to a new whole. Nor is it certain that the structure and meaning that initially emerges in conjunction with opening a dimension of variation in the experience can be experienced (by the student) as *relevant* in the domain where they conceptually consider the object of learning to be located. Together we call the episodic threads where students go through these two stages (with respect to some learning object) a thread of learning.

Building on this we asked what characterised the variation that students experienced in the successful threads of learning – was it always the same kind of variation*?* We could recognise two distinctly different kinds of variation – whether the variation concerned the internal structure (and meaning) of a part or the variation concerned the relationship between parts.

We thus classified the experienced variation into two categories:

- variation *within* an aspect – different things are present to the learner in an aspect, for example, in a representation.
- variation *across* aspects – for example, when different representations are recognised as distinct, but portraying different aspects of the same concept. This implies that several aspects are discerned simultaneously, and that the same physics construct is appresent to the learner in several representations.

To illustrate our results, four example 'threads' will be given. They range in length from a single episode to six episodes. In order to limit the relevant context, they are taken from only two sessions: the first thread from one session, and the other three from another. The three students quoted are here named using pseudonyms – Alex, Berne, Caine.

Example 1 – From four to six and thus infinity

Consider the introductory illustrations of emission (Figures 2 and 3) , and an associated tutorial question (Figure 4), that the South African students in our study had met.

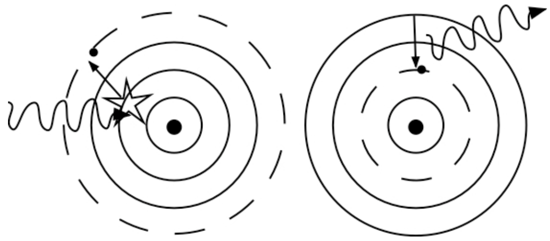

Figure 2. *Introductory textbook illustrations of absorption and emission set around four equally spaced orbits.*

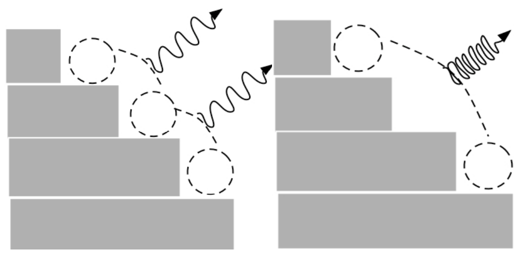

Figure 3. *Introductory textbook illustrations of emission set around four energy steps of equal height.*

Consider just four of the energy levels in a certain atom, as shown in the diagram. How many spectral lines will result from all possible transitions among these levels? Which transition corresponds to the highest frequency light emitted? To the lowest frequency?

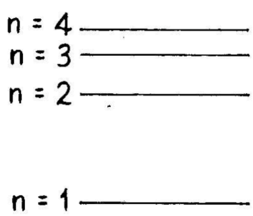

Figure 4. *Tutorial question set around a set of four differentially spaced energy levels.*

The illustrations shown in Figures 2, 3 and 4 show different aspects of the Bohr model of the atom, showing variation for example between picturing transitions between orbits, transitions between energy levels, and the spacing of energy levels. The number of levels or orbits shown is not varied though – four levels are used as a convenient finite illustration of the infinite number of levels in the model.

The extract below is of a student expressing the experience of these illustrations and type of tutorial questions, contrasted with the experience with the simulation:

Alex	Yes, this is what I learned from this. In my tutorials, my past tutorials, when we were doing this subject, there were like a line from like E1 to E4, there were no more than that, then I get surprised when I see E1 to E6, you see, [...]
Researcher	Okay, so you're saying when you did the tutorials you thought that there could only be four energy levels
Alex	Yes, then this [six energy levels present in the computer simulation session] tells me there is no limitation.

Alex took the four energy levels as given (Figures 2, 3, and 4), but working with the simulation, where six energy levels are shown (Figure 1), has opened the aspect of the number of energy levels to Alex ('*I get surprised*'). As a result Alex sees that there are actually an infinite number of possible energy levels *('there is no limitation').*

In the single episode presented in this thread of learning Alex spies a dimension of variation within a particular aspect (the number of energy levels) in different portrayals of the Bohr atom, and immediately recognises a meaning, which makes sense in terms of the whole: the number of energy levels is actually unlimited, but may be portrayed with a limited number.

Example 2– Relating energy to wavelength in terms of the three representations

The remaining three example threads of learning are taken from the same session, which was especially rich and clear. To allow appreciation of the distribution and timing of episodes, consecutive numbering of the statements in the session is presented on the left. This entire session had around 500 statements and lasted approximately 60 minutes.

The first of six episodes in this thread of learning starts with the students Berne and Caine reading tutorial Question 1:

10.	Berne	[Reading] Does it take more energy for the electron to change from the ground state [to the second orbit] or from the ground state to the third orbit? Which transition requires the shorter wavelength photon? [End of question.] OK.
11.	Caine	The second one. [Clicks E1->E2]
12.	Berne	There we have a difference in approximately 10 electron volts
13.	Caine	Yes
14.	Berne	And from the ground state to the third orbit ... [Clicks E1->E3] and there it, the difference it is 12, if we compare the wavelength then it's 102 nanometres ... and we see that the transition between one and three requires the shortest wavelength.

15.	Caine	Yes

In the above the students (in particular Berne, who sounds quite bored) do not approach the task as an opportunity to learn something new, but as a recording exercise to collect the correct answers of the questions. Where is the focus of the students? The two energy differences of the two transitions (E1->E2 and E1->E3) are in focus, and are compared (as two numbers). Likewise the two corresponding wavelengths are compared, without consideration of the variation inherent in considering these two comparisons one after the other. Thus the relationship between the two representational formats (energy and wavelength) is not in focus, or seen as an essential variation in the situation. With respect to the situation as discerned by Berne and Caine, the variation is not critical.

33.	Berne	Ok, next question. [Quiet, reading question] [Reading Question 3 half-aloud: 'Which electron transition will emit the longest wavelength photon?'] The longest wavelength
34.	Caine	Shouldn't that be 6 to 5?
35.	Berne	Yeah, I think so. [Caine clicks E1->E6->E5, the rightmost spectral line (having red colour) blinks] The shortest, its the longest, isn't it?
36.	Caine	It's the shortest.
37.	Berne	No, the longest. No, isn't it from 1 to 6 now? [Caine resets to E1 and clicks E1->E6, causing the leftmost spectral line (blue) to blink.] They have the highest difference. [Points to the orbital diagram, indicating the distance between innermost and outermost orbit with two fingers]
38.	Caine	But we want the smallest difference.
39.	Berne	Yeee, let's, hehe, I have been studying too much mechanics [The students, who have just had a mechanics exam, exchange looks, and chuckle.] Which electron transition will give the longest wavelength photon. OK, then we want the shortest. If we have long
40.	Caine	It's little energy
41.	Berne	It's little energy
42.	Caine	And it should be 6 to 5 [Clicks E6->E5].
43.	Berne	Yeah, that's what I hope we have [Points to energy level diagram]
44.	Caine	That's true.

In the above, we interpret that Berne interacts (lines 35-37) with a dimension of variation inherent in the relationship between energy difference and wavelength (which is a central aspect of the Bohr model), in contrast to the previous episode, where this relationship was not thematised at all. However, the structure of that relationship is taken for granted as having the meaning of a direct relationship (for example, in contrast to an inverse relationship). While Caine states the expected answer (line 34), and clicks in order for this case to appear on the screen (comment line 35), Berne hesitates and first states that it is the shortest wavelength, then seems to notice that the wavelength blinking in the spectral line is actually the longest (end line 35). Caine seems confused (line 36), and Berne then notices another unexpected detail: the transition which gave the longest wavelength was not E6 to E1, but E6 to

E5 (beginning of line 37). Caine starts to click to make the E1->E6 transition to show, while Berne motivates why this transition should correspond to the highest wavelength (end of line 37). When this does not give the expected result (instead the shortest wavelength is indicated), Caine contradicts Bernes motivation with the opposite (line 38), and Berne agrees, slightly embarrassed. They then go on to check that this is the case (lines 39-43), almost stating a possible relationship between energy and wavelength (long wavelength corresponds to little energy). Nevertheless, they do not explore the nature of this relationship but, judging from the discussion, the meaning of such a relationship is not constituted in the students' experience, and thus not recognised as important. Rather the meaning is seen as limited to the present case – as contextual. The capability to consistently see the relationship between energy and wavelength in similar, but different contexts, is not developed, as is clear from the following episode, which occurred later:

71.	Berne	[Reading Question 5: 'The transition from the 2nd to the 5th energy level required a photon of wavelength 434 nm to be absorbed,] which is blue. Adjacent to [To the right of] this blue line, there is a green line. This line is also due to a transition involving the second level. What other level is involved in the green line transition: the fourth or the sixth?' [End of question.] Eehh, here we need more energy [Points to green line in spectral diagram.]
72.	Caine	Yes
73.	Berne	And then we have to go up one line further. [Points to energy level diagram, indicating transition E2->E6.] Right?
74.	Caine	Right. Test. [Clicks E2->E6, making the blue to the left of the blue line to the left of the green line blink.]
75.	Berne	No. The other way around. Now we got that blue one.
76.	Caine	Yes.
77.	Berne	Yeah, and yeah. That's yeah, here in energies [Caine: mm] they go from high energy [Points to the left of the spectral diagram] to low energy, [Points to the right of the spectral diagram] not the other way around. Yes. [Caine clicks E2->E4, and the green line blinks.]

In the above episode the students are once again addressing a tutorial question (this time Question 5) concerning the relationship between the energy difference and wavelength. They predict (lines 71-73) that in order to get a longer wavelength photon, they need a larger energy difference – the opposite to the relationship they almost stated in the previous episode (lines 33-44). They are proven wrong by the simulation (lines 74-75). This causes Berne to explicitly consider the relationship between the energy diagram and the spectral line diagram, voicing sort of an inverse relationship (line 77). This indicates that they discern the basic nature of this dimension of variation, but the consequences of this kind of structure of the relationship is not explored further. When they revisit Question 5, below, they are further negotiating the meaning of the relationship:

135.	Berne	[Question] five. The green line [in the spectral diagram]
136.	Caine	[It was the level] four [to level two transition], wasn't it?

137.	Berne	Four, since more energy [Clicks E2->E4, the green line blinks] is required. ... Four instead of six.
138.	Caine	Six
139.	Berne	From two to six, what does that produce?
140.	Caine	That should be the [Indicating the blue line two to the left of the green line in spectral diagram with mouse pointer]
141.	Berne	Yeah, then it's the green line since its less energy.
142.	Caine	Yes
143.	Berne	Ok, yeah [writing on paper]
144.	Caine	Two to four
145.	Berne	Two to four. Ok

Returning to Question 5 in anticipation of the discussion with the interviewer, they are again inspecting the variation between choosing a transition corresponding to more energy and a transition corresponding to less energy (lines 139-141). The structural component in their experience that is developed here is related to what consequences moving left or right from one line in the spectral diagram to another has in terms of the corresponding energy difference – left in spectral diagram means less energy difference, right means larger energy difference. In the interview, faced with the task of further explaining their reasoning related to Question 5, the essence of the dimension of variation is further reconstituted, in particular for Berne:

231.	Berne	Often the spectrum [Points to spectral diagram] is drawn the other way around. [Caine nods in agreement] Starts with the red and go to the blue, I am used to that sort of spectrum
232.	Researcher	So why is it that there is a difference here?
233.	Berne	You, yeah, because they are [Points to spectral diagram], well, what do you call it, closer to each other here [Points to the left part of the spectral diagram] and because, why, because you want to show, yeah, you start with the energy transition between [Points to energy level diagram] one and two, one and three
234.	Researcher	Yeah
235.	Berne	And the first one to six [Looks at screen] produces the most, you can't have any more [Points to left of spectral diagram], you can't have any lines to the left of this spectrum
236.	Researcher	So it's the, so it's for pedagogical reasons?
237.	Berne	Yeah, kind of, and its easier if we want to expand this one to one more shell
238.	Researcher	Ok
239.	Berne	No, one more shell, then you get one line there [Points to the left of spectral diagram] and some more on that side [Points to the right of spectral diagram], so that can't be the answer. [General laughter] Then, can it be like this instead? That often you go left, means low

240.	Caine	Yes
241.	Berne	Often in whatever you use, on the ruler whatever, and this [Points to right part of spectral diagram] relates to high energy but short wavelength, yeah, and then you have arranged it in increasing wavelength instead of increasing energy.

In the above, Berne starts to explain (line 231) that an inverse relationship between energy differences and the spectrum is confusing since there often is a direct relationship (proportionality) – this is the case when the spectrum is drawn in terms of frequency (which Berne seems to equate with energy since they are directly related) instead of wavelength as it is done here. In response to a question from the researcher (line 232), Berne attempts to explain the difference between these two kinds of spectra. In that explanation, Berne opens up another dimension of variation – the relationship between characterising a photon in terms of frequency or wavelength – and by that moves towards loosening the experience of the spectrum from one particular representational form (frequency or energy were in the previous episodes taken for granted as the basis for drawing the spectrum). That explanation (line 233-237) and the reflection that follows (line 239) make explicit the exploration of the consequences of potential (imagined) variation of the number of levels considered (seven instead of six) for the holistic relations between the three representations present in the simulation (orbital diagram, energy levels, and spectrum) – having an additional energy level implies spectral lines *both* to the left and the right compared to the present spectrum. The meaning of these relations as previously seen by Berne is deemed insufficient ('*that can't be the answer*', line 239) and renegotiated. Or in other words, new meaning is given to the dimension of variation regarding the relationship across the aspects of Bohr's model pinpointed by the three representations, having at its core an inverse relationship between energy and wavelength. This episode contrasts to the previous episodes along this thread of learning, by further reconstituting the structure and overall meaning of an inverse relationship between energy and wavelength and by opening and simultaneously considering several additional dimensions of variation regarding the relationship between the different representations and their internal structure. In the final episode in this thread of learning Berne elaborates on the structure of understanding that has been developed in this thread:

290.	Researcher	But you said that if you add another shell, then you will actually add some [lines] on both sides?
291.	Berne	Yeah, since the energy gaps [Points to energy diagram] get smaller and smaller, to get almost continuous as you write in the end, I think. [Indicating paper with question texts.]
292.	Researcher	Yeah
293.	Berne	Yeah, and since we have a smaller energy gap, it will relate to a, the longer wavelength, which will produce one out here. [Points far to the right of spectral diagram.]
294.	Researcher	Yeah
295.	Berne	And since we have one more energy level [Show an imagined level in the air], we have more, larger energy difference between the lines, the first and the last one, and it will produce a line to the left.

The imagined variation of adding an energy level (in this and the previous episode) allows Berne to holistically relate the three diagrams and their meanings to each other, as well as their structure and relationship.

Example 3– Exploring the apparent variation in spacing

The next thread starts early in the session where Berne has made an interesting observation and opens a dimension of variation without any apparent plausible meaning:

45.	Berne	Mmm, but I compare the differences here. [Berne points to orbital diagram and then to energy level diagram, Caine: Oh] The distances and there, they are not good [chuckles] to compare really [Caine: No], since we shouldn't compare them here.
46.	Caine	Yes
47.	Berne	We could use the cursor instead. The cursor instead. [Points cursor to top of energy level diagram.]
48.	Caine	Yeah
49.	Berne	Once you think you know the excited energy [Reading, silence 20 seconds] ok, an interesting observation is that [Reading, inaudible] ... Yeah, they get closer and closer together. Closer and closer together. [Points to centre of orbital diagram] ... They get closer and closer together here [Caine moves cursor. Caine: Yes] but that, [Points to lower part of energy level diagram] ehh [hesitation, Berne takes mouse], the transition here [Points with cursor on E1->E2] between, that and that one is the transition between E1 and E2 and here [Points with cursor to E1-E2 distance in energy diagram] we have a huge distance, [Caine: Yes] here [Points with cursor to distance between two innermost orbits in orbital diagram] we have a small one [Caine: Yes]. Is that correct?
50.	Caine	Yes, it is. [Nods]
51.	Berne	Am I thinking in the wrong way now? [Reading]... In energy
52.	Caine	Yes
53.	Berne	Yes, they get closer together in energy here [Berne points to screen Caine: Yes] and they are not linearly spaced in energy. [Silence 50 seconds, then the students go on to the next question.]

After opening a dimension of variation around the increasing spacing between the levels in the orbital diagram (45), Berne spends some time exploring and expounding (47), articulating critical differences between the pattern of the spacing – the energy level diagram goes from large distances between levels to small, while in the orbital diagram distances go from small to large. Perhaps because of lack of confidence, the topic is dropped and the students go on to the next question without even a comment. They nevertheless return to the topic later (361 and onwards) in a discussion with the researcher, now more persistently exploring to find a plausible meaning, relevant to physics, in this dimension of variation:

361.	Berne	I don't know if we should have realised that, but the distances here [Points to the energy diagram] between gets smaller and

		smaller and [we] have gotten, what do you call it, explanation for that in the text.
362.	Researcher	Why is it that the distances get smaller as [Points to orbital diagram] you go versus the nucleus?
363.	Berne	I have got explanation for this [Points to energy diagram] and this [Points to spectral diagram], but I have not gotten any explanation for that one [Points to orbital diagram]
364.	Researcher	Ok, what is then the relationship to this diagram [Points to energy diagram]...
365.	Caine	Larger energy for the smaller gap here, [Points with mouse to centre of orbital diagram. Researcher: Yeah] particularly the big gap here is away from the core [Points in orbital diagram to outermost orbit].
366.	Researcher	Yes, do you have any reasoning around that?
367.	Caine	It is longer away from the positive core so its not affected so much

Berne and Caine search for meaning across several aspects and representations of the phenomenon: the discrete spacing in the three representations and their different natures – increasing in the orbital diagram, decreasing for the energy levels and seemingly random but related to possible energy differences for the spectral lines. The discussion goes on for a while, exploring the issue in different ways, searching for a relevant and plausible essence of the variation. Then suddenly the researcher 'hits gold' and opens the way for further learning outcomes with a focal reference to space:

410.	Researcher	And why they [the orbital diagram and the energy diagram] are different? [Silence 10 seconds] Because this one [Points to orbital diagram] is supposed to be in physical space, its physical spacing [Silence 8 seconds]
411.	Berne	Yeah, but if we look at the energy diagram [Points to energy diagram] don't you have the same thing if you, what do you call it, travel with a space shuttle from the earth, look at the potentials
412.	Caine	Yes
413.	Berne	If we have a, take the potential gravitational potential at same distances you will get something like this [Points to energy diagram], that they get very close together further out from the earth
414.	Researcher	Yeah, so that would explain if you would have equidistant energy levels or shells, you would have something different in the other, in the energy. If you have equidistant, the same distance between each shell in physical space, you will have different energies, because there will be, they will correspond to the potential
415.	Caine	Yeah
416.	Berne	Yes, and the potential is due to the attracting force from the nucleus and the force, isn't it something, isn't that one proportional to the distance squared?

After exploring different lines of reasoning, the researcher comes with a pivotal statement (line 410), which creates a connection in variation within physics and its explanational patterns to space, and gravitation. This is accepted as an analogue meaning, lending itself to constitute a physics relevant meaning for the opened dimension of variation across aspects. This meaning is not only seen across the aspects present in the three representations in the simulation but also in relation to aspects of gravitation. In this way, the structural components of the dimension of variation are tied to similar structures in another field of physics, creating the experience of relevance. The researcher confirms the explanation from Berne, and further points to components in the relationships between the distances (414). In the final statement (416), Berne starts considering mathematical similarities between these situations, further trying to pinpoint the parts of the relationship.

Example 4 – Finding local relevance

The final example thread of learning is branched from the second example. In the episode below, the students are trying to find a way of determining the ordering of the spectral lines in terms of the energy differences between different energy levels:

95. Berne Eeh, ... the how [Points] from one to six is that one, right.

96. Caine Yes

97. Berne One to five the other [Points].

98. Caine Mmm. [Click, click] ... Yes

99. Berne And the third one is that one. ...

100. Caine Yeah [Click, click]

101. Berne Fourth. [Click, click, click]... Yeah, you see the pattern.

102. Caine Yes

103. Berne OK, then this is [Points] levels two to six, which one was that [Click, click, click]... that one, then this one is two to five, two to four, two to three, then this is three to six,

104. Caine Yes

105. Berne And that one is three to five [Points, Caine clicks]. ... OK and then that is three to four, [Click, click] yeah

106. Caine Yes

107. Berne Then we have seen the pattern. What transition produces this line, its three to four

108. Caine Yes

Here, Berne and Caine open a dimension of variation focused on the relationship between the two diagrams (energy levels and spectral lines). The 'meaning' of the relationship is considered in isolation from the meaning of the different diagrams (or from the meaning constituted about their relationship considered in the previous example thread of learning). In this respect it is a consideration of a dimension of variation within a single aspect of the Bohr model and attributing a meaning to it, which is not very relevant in terms of physics (as experienced by the students during the session). Thus, this thread of learning lacks the second stage in our model of the process of learning with respect to learning *physics*. The thread nevertheless seemingly comes to a closure with an experience of (local) relevance – in the context of being able to (semi-)predict the answer to the tutorial question.

	Example 1	**Example 2**	**Example 3**	**Example 4**
No of episodes	1	6	3	1
Learning object (meaning constituted)	Unlimited number of energy levels	Seeing the three representations in terms of inverse energy-wavelength relationship	Principle for spacing of orbits, energy levels, and spectral lines	'Counting pattern', meaningless with respect to physics
Within/across aspects	Within	Across	Across	Within
Key variation experienced	Seeing a portrayal using six levels (in contrast to portrayals using four)	Imagined variation of an additional energy level, exploring consequences for the three representations	Difference in spacing in the three represen-tations	Which spectral line belongs to which transition?

Table 2: *Summary of the four examples given.*

Discussion

Reflection on the method of analysis

We have now offered four different threads of learning to illustrate our data and results (summarized in Table 2). The learning process is characterized through a number of critical episodes, within which we argue new understanding develops. We have found threads of learning, such as those exemplified in the Results section, which are recognisably successful in the sense of developing a capability to see an object of learning in a more holistic and meaningful way, across the whole of our empirical material.

Within the phenomenographic tradition, the research interest of investigating how students handled different learning tasks is not new. In the early phenomenographic work (Johansson et al., 1985; Marton et al., 1977; Marton & Säljö, 1976) this interest was channelled into the description of learning as change between qualitatively different conceptions and into describing approaches to learning. This was criticized for only being a 'static' description of the process of learning. For example, not describing events or mechanisms in the process as such, which may be because the available developed theoretical framework did not describe *how* learning took place

Our analysis is a return to this research interest, now drawing on the theoretical developments around learning and experience, attempting to bring out a 'dynamic' description of the process of learning – for example in exploring how experiencing variation shapes the process. It is taking a temporal aspect of the process into account, but retaining focus on learning, on the experience of the learner and on variation with respect to the phenomenon. It analyses on a different level than the analysis of 'approach' (for example, Johansson et al., 1985; Marton et al., 1993; Marton & Säljö, 1976; Säljö, 1979), in that it attempts to follow what is in focal awareness for some students, on the basis of what is said by the students, their actions and what they can convey about the process, when asked in action and afterwards – looking at a micro-level. It may be said to empirically try to 'resolve' students' otherwise unthematised shift between one way of experiencing something to a qualitatively different and potentially more powerful way of experiencing something.

As might be clear from the illustrations given in the results section, we compared different parts of the same session, where similar context and focus might support, contradict or clarify our interpretations. It was also important to reveal to what extent a *capability* to see this aspect in a new way had been developed. To put it differently, we looked for a certain degree of consistency in the way the students were handling different situations (a degree of contextual appreciation, Linder & Marshall, 2003), in order to be able to judge that something in accordance with what we call learning had been occurring. In that interpretation, it was possible to recognise that the constituted understanding was meaningful to the students only when they were able to link the experience of something to a meaning that was relevant in the context they expected in the (pedagogical) situation, i.e. in this case that the students could recognise their new understanding as acceptable in the context of physics as they understand physics. In theoretical terms, the students' learning process was connected to a successful linking between an experienced pattern of possible variation in the phenomenon, and an experienced meaning, attributable to physics. Learning which had an aspect of contextual appreciation thus presupposed the *experience of relevance*.

Comparing our approach to that of contemporary discourse analysis, for example by Wickman, Östman and co-workers (Lidar et al., 2006; Wickman, 2004; Wickman & Östman, 2002a, 2002b), which employ a 'high-resolution' analysis to develop an 'understanding [of] learning on a discourse level, i.e., how meaning changes during discourse' (Wickman & Östman, 2002a, p. 601), our analysis brings out the students' interaction, experience and grappling with the object of learning, rather than inter-discourse relationships. However, the empirical-analytical starting point for Wickman and Östman (2002b, p. 466) in investigating 'how university students generalize during practical work and to what degree they use observations for this purpose' bear interesting similarities to our work – a focus on the learning process, the use of similar empirical grounds, but the use of a different theoretical framework to interpret student communication and interaction. Wickman (2004, p. 326), for example, sees learning 'as a journey, where the direction is influenced by the encounters students experience along the way'. This can be compared with our focus on learning as coming to discern an aspect within the whole and relating it to other aspects, in a series of critical episodes.

Implications

An article such as this carries many implications: from those directly emerging from the focus of the article, to those emerging from interesting anecdotal pieces of data that also emerged during the analysis. As a result of our study there are two threads of implication that we think would be worthwhile for teachers who take on a variation perspective to view student learning to consider. The first is situated around how students come to discern things in a simulation context. Here we found that the learning outcomes possible for the students are dependent on the focus that is adopted. Since a detailed exploration of this aspect may be found in Ingerman et al. (2007) we will not repeat it here.

The second is situated in a temporal dynamic that we found in the path of learning. The current descriptions of 'variation theory' to be found in the student learning literature are principally embedded in teacher action. This teacher action can be seen to carry the implication of a learning spontaneity for students who, through variation, discern critical features of an object of learning. Our data, however, suggests that there is far more likely to be a temporal than an instantaneous dynamic, for example, see the earlier data descriptions labelled lines 33-44, 71-77, 135-145 and 231-241 and their associated discussion. Thus teaching design should anticipate such temporality and with that the capability to consistently see the critical attributes and relate them appropriately, particularly across contexts, should not be too readily anticipated.

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