EXPLORING THE PROCESSES OF STUDENTS' DEVELOPMENT OF PHYSICS CONCEPTS

Recent research on conceptual change has aimed to describe how students enrich, restructure, or revise their conceptual knowledge. Current theories on conceptual change often stress that within a learning process students create synthetic models which are based on students' prior knowledge and their assimilation of new knowledge. However, little research has focused on the criteria which can be used to describe what kind of knowledge is assimilated (and what is not), how students' situated understanding relates to the knowledge assimilated and how in detail students' knowledge develops within and in-between situations. Research reported in this paper, therefore, seeks to explore and theorize criteria which can be used to analyse the quality of students' current knowledge, the quality of the learning material, and the development of students' knowledge and their concepts during a learning situation. The dynamics of students' conceptual development were investigated by means of a detailed video-analysis. The paper draws upon theoretical arguments for such kind of investigation, empirical procedures and outcomes as well as upon implications for further research and science teaching.

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Concepts about Conceptual Change

Research on science teaching and learning has focused on students' conceptions and on teaching strategies that promote conceptual change (e.g., Duit, 1999; Duit, 2004; Duit & Treagust, 2003; Limón & Mason, 2002; Tyson, Venville, Harrison, & Treagust, 1997). Within such research, tests and interviews are widely used in order to assess students' conceptions prior to and/or after instruction (e.g., Hake, 1999; Hestenes, Wells, & Swackhamer, 1992). Even though the theoretical frameworks may differ in some details, most of them share a common body of general assumptions which are:

- ☐ Most of students' activities and utterances have a theoretical foundation (e.g., knowledge is organized in concepts or in framework theories).
- ☐ Students entering a physics classroom will have prior concepts (framework theories).
- ☐ Students' conceptual knowledge will not necessarily match that of scientists, that is, students may hold misconceptions (naïve frameworks).
- ☐ Students' conceptual knowledge can change when they are shown contrasting "correct" concepts.

Although the notion of "concept" is at the core of the assumptions presented, the usage and theoretical account of "concepts" has recently been debated in the literature (e.g., diSessa & Sherin, 1998; diSessa, 2002). Is all knowledge that students can have (and show) conceptual? If not, what distinguishes "simple" knowledge from concepts? Typically, "conceptual" knowledge is considered in contrast to procedural knowledge, arguing that conceptual knowledge refers to an "implicit or explicit understanding of the principles that govern a domain" whereas procedural knowledge refers to "action sequences for solving problems." (Rittle-Johnson & Alibali, 1999, S. 175). However, even if only knowledge is taken into account that can be expressed verbally, one may still ask whether or not all such knowledge is conceptual in a sense that it considers the principles that govern a domain (see also diSessa & Sherin, 1998). It probably makes a difference whether a child just repeats that this particular object is her baby chair (being told by her mum) or whether she can express that all chairs have an area to sit on and (typically) four legs. Also in physics we may distinguish between knowledge that is tied to particular objects and situations (descriptions, labels) and knowledge which refers to the commonalities of several objects and situations and may, therefore, be considered as "conceptual." When ascribing concepts to a learner's utterances (or activities) we tend to forget that these concepts are only the researcher's construct: the subject behaves as if she holds that particular concept (framework theory). Seeing a concept or a theory in almost every activity or utterance an individual develops reduces the number of interpretations that are possible: "Sentences are taken to represent theories, and words are taken to represent concepts, ignoring the diversity in types of concepts or theories that we would expect." (diSessa, 2002, p. 37).

Conceptual Qualities

In current conceptual change research it is mainly the established scientific concepts that serve as a "measure" for quality. Such a position is, therefore, a normative one: students' conceptual understanding is compared to that of scientists. Students can hold misconceptions, everyday concepts, naïve frameworks, synthetic models, or inappropriate ontological categories (e.g., Chi, 1992; Vosniadou, 1994). The "nearer" students' concepts are to those of scientists, or the more scientific elements are included, the "better". However, this seems to be a limited understanding of quality, which also limits the way in which conceptual change is investigated. Comparing, for instance, "Simple electric circuits can be described with the Ohm's law." with "An increase of amperage results in an increase of resistor's temperature and, therefore, voltage does not increase proportional to amperage." demonstrates that both descriptions are conceptual and are in accordance with current scientific ideas, but the latter is a more precise and expanded concept. The example may indicate that we need to describe students' knowledge not only with respect to scientific norms but also with respect to the quality of students' understanding. Using the notion "concept" only for knowledge that governs a domain would be one opportunity to distinguish between different qualities (other distinctions can be found in e.g., von Aufschnaiter & von Aufschnaiter, 2003). Arriving at any kind of conceptual understanding would then be an important improvement even if the concept does not include the scientific point of view.

Conceptual Change

In the early years of conceptual change research, "change" was considered as a sudden shift in which students replaced their prior concepts with a new scientific concept (e.g., Duit & Treagust, 2003). During the last years an increasing number of researchers have stressed that conceptual change is a rather gradual and slow process. However, it remains unclear to what (time) scales "gradual" and "slow" refer: changes within minutes, hours, weeks, months, years?

Typically, it is assumed that students enter school holding specific theories, concepts, or ontological categories. During formal and systematic instruction students either enrich and improve their knowledge which may be a reason for misconceptions or they develop synthetic models in which they combine their initial frameworks with assimilated information (e.g., Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou, 2001; Vosniadou & Verschaffel, 2004). Neither does research seem to consider that students may not have any kind of conceptual knowledge concerning a particular topic nor that students' theoretical knowledge is a result of (partially systematic) "instruction" of their everyday world. Therefore, research rarely focuses on how in detail students arrive at any kind of theoretical understanding (maybe being naïve) or what kind of (systematic) instruction supports or hinders such development.

A Different Perspective on Concepts and their Change?

From a psychological point of view one may argue that even though students' knowledge does not directly indicate a conceptual understanding, (unconscious) mental activities "behind" the expressed knowledge refer to concepts, that is, different types of knowledge or different qualities can be processed in parallel. At the moment it is impossible to evaluate empirically whether or not this is a valid assumption, however, there are some arguments indicating that such a description is not very helpful to understand (mental) activity and learning. From the *acting individual's point of view* several activities can take place without knowing about the conceptual grounds. Other than stated by Vosniadou and her colleagues (e.g. 2001), I would stress that in order to function in the world students (or all humans) do not necessarily need a (coherent) *explanatory* framework. There is no need to explain the function of a switch in an electric circuit or how pictures emerge on a screen in order to switch on the light or use a computer. To do the washing up, we do not need to know about surface tension, nor about the role that washing-up liquid plays in reducing the surface tension which enables any fat to dissolve more easily. From an *observer's point of view* one might argue that even though an individual's (verbal) activities can be described as if these activities follow a certain concept this does not say anything about the mental reality of these concepts (e.g., Neuweg, 2002).

Taking all issues raised into account, a somewhat different position on conceptual change may be considered in which knowledge does not necessarily need to relate to concepts. From the arguments given above, it can be assumed that concepts emerge from (intensive) explorations of particular situations:

(1) Students' activities and statements emerge without a theoretical foundation: "I'll just try it this way" (*explorative* approach).
(2) Students' activities and statements are based upon an intuitive understanding developed through prior activity: "I don't know why it works but I know it does" (*intuitive rule-based* approach, see also e.g., Stavy & Tirosh, 1996).
(3) Students express theoretical knowledge explicitly: "It is always like this because in such cases always a …" (*explicit rule-based* approach).

In accordance with Rittle-Johnson and Alibali (1999) it can be expected that (3) relates to a conceptual understanding which may have different qualities depending on the concepts and their interrelationships developed. Also, from an observer's perspective it might be argued that (2) includes (an implicit) conceptual understanding. However, as this understanding is not yet explicitly present to the learner, (2) might be seen as some sort of "transit" towards conceptual knowledge. It should be stressed at this point that, certainly, even young children can and will develop concepts through (extensive) experiences with particular aspects of their world. These concepts are based upon fundamental distinctions and classifications of everyday experiences, thus, might be developed in processes such as suggested in (1)-(3). However, there are several topics or aspects which are introduced to children at school yet unfamiliar to them (like the function of a diode in an electric circuit or a neon bulb to determine different types of charges). Here, we cannot expect extensive prior experiences and, therefore, conceptual understanding.

Main issue addressed in my recent research is the empirical validation of the criteria and the development given in (1)-(3). In order to develop a more precise description of students' development of science concepts, data on students' learning of electrostatics were used to set up a system of categories describing conceptual development and the quality of the concepts developed.

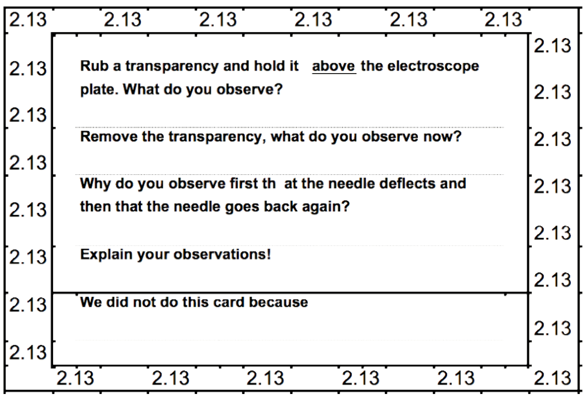
Sample, Procedures, and Methods

Even though learning is considered as a gradual process, current empirical investigations rarely focus on this process explicitly. The notion "process" seems to refer to "small" scale comparisons between pre- and post-concepts (just a few lessons in-between) or to concepts that are determined using interview techniques (e.g., Hestenes et al., 1992; diSessa, Elby, & Hammer, 2002). However, in both cases researchers tend to search for more or less stable concepts rather than tracing students' development (or change) of these concepts. Especially interview techniques may reveal how students incorporate their existing knowledge in varying circumstances (e.g., the researcher's different questions) but they cannot (fully) clarify how (and which) knowledge being constructed within the interview is learnt (applied later on). Therefore, a distinction between the processes of assessment, that is, students situated development of knowledge including small scale revisions, and processes of long term revisions within several successive learning units might be useful.

For the last years, we have concentrated on experimental studies with small groups of 2-3 students each aged between 13 (which is grade 8 in Germany) to about 27 (PhD-students in physics). In total, we had five studies each with nine to ten groups from grade 8, grade 11, and after grade 13 as well as two cohorts from University (e.g., von Aufschnaiter & von Aufschnaiter, 2003). Each study comprised three to five sessions lasting about 90 minutes at a weekly basis. Topic of all studies was electrostatics and, for the students after grade 13 and at University, electrodynamics. In order to compare processes between and within cohorts, we presented all tasks and all additional instruction, which focused on theoretical explanations, on cards (see Figures 1a/b). This paper reports on results for in total 14 groups of our lower and upper secondary population (grade 8 and grade 11) where each groups consisted of three students. The tasks and instructions for in total three sessions focused on:

- ☐ Material/objects that can be charged, attraction and repulsion of such material, and the different types of charge (19 tasks/22 instructions).
- ☐ The neon bulb to determine charge and its polarity (13 tasks/5 instructions).
- ☐ Charging and induction of an electroscope (12 tasks/5 instructions).
- ☐ Charging and discharging of an electroscope with induction and grounding (7 tasks/3 instructions).

Most of the tasks were based on experiments so we also provided several materials that could be used to carry out the experiments.


2.13

Rub a transparency and hold it above the electroscope plate. What do you observe?

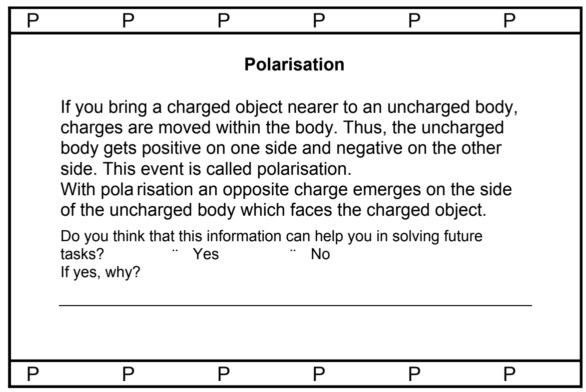
Remove the transparency, what do you observe now?

Why do you observe first th at the needle deflects and then that the needle goes back again?

Explain your observations!

We did not do this card because

Figure 1a. Card number 13 from the second session.


P

Polarisation

If you bring a charged object nearer to an uncharged body, charges are moved within the body. Thus, the uncharged body gets positive on one side and negative on the other side. This event is called polarisation.
With pola risation an opposite charge emerges on the side of the uncharged body which faces the charged object.

Do you think that this information can help you in solving future tasks? ¨ Yes ¨ No
If yes, why?

Figure 1b. Instruction P provided to students in the first session.

Figure 2. Video-picture from 11th graders (about 16 years old).

All sessions were video-recorded so that individual student's understanding could be investigated in great detail (see Figure 2 for a typical picture). In order to develop a system of categories and apply the system to the data, minutes instead of detailed transcriptions were used so that more data could be analysed. The difference between the minutes and a detailed transcript mainly refer to two aspects: (1) minutes summarize students' activities instead of giving a detailed description of these activities. For instance, a transcript would say "Student S takes rod and cloth, rubs rod with the cloth, puts cloth down. Student A touches rod with neon bulb." For the minute, the scene would read as follows: “Students rub rod and touch it with the neon bulb.” (2) Ongoing discourse is summarized as long as it refers to students’ activity directly (how to hold a rod, what material to use next). Utterances referring to physics in particular are cited but without pauses, repetitions etc. (an example is given in Table 2).

For a more detailed set of codes data were first roughly divided into explorative, intuitive rule-based, and explicit rule-based. Then, for each category codes were extracted from the data and evaluated with further data. Resulting codes and their description are presented in Table 1. In about every 15-30 seconds of the video a code is ascribed. Previous research has revealed that within this span of time students develop a coherent line of thought that can be ascribed to one code (e.g., von Aufschnaiter & von Aufschnaiter, 2003). Thus, conceptual development is traced on the basis of less than a minute and allows, therefore, a detailed picture of the dynamics to occur.

So far, the codes fully apply to the high school students and were also used successfully in another study on learning processes of University students (Neumann, 2004). However, more or other codes might be needed for other settings, more experienced learners, or other physics topics.

Table 1. Categories, Codes, and Examples on Students’ (Conceptual) Knowledge

Category	**Codes**	**Description**	**Example**
explorative	Experimen**T**	Students carry out an experiment (and/or describe what they observe).	S: Lets try it and see what happens (rubs rod and holds it above the electroscope)
	Mental **E**xperiment	Students “remember“ a prior experiment (and/or describe what happened).	S: While holding the rod above the electroscope, the needle deflected.
	DEscription	Students use linguistic elements (of any type) to describe observed/remembered phenomena or objects.	S: Wow, through some magic process the needle deflected.
intuitive rule based	**E**xperience-**B**ased	Students express an assumption about what will happen.	S: The needle will also deflect when we use a rubbed transparency instead of a rubbed rod.
	Statement-**B**ased	Students refer explicitly to a statement which is important from their point of view.	S: But the instruction says that you should rub it on the electroscope plate.
	ATtribution	Students make use of specific linguistic elements (physics terms) to describe observed/remembered phenomena and objects.	S: The needle deflected because there are electrons on the rod which move to the electroscope.
explicit rule based	**GE**neralisation	Students express a generalisation explicitly.	S: The electroscope can be used to determine charge.
	EXplanation	Students develop a rule which is based on the connection between two or more aspects (one of which is a generalisation).	S: A material is charged, when the needle of an electroscope deflects while holding the material above or on the electroscope plate.
	HYpothesis	Students explicitly predict the result of an experiment on the basis of rule based connections.	S: The needle of the electroscope will deflect because material which is charged negatively has a surplus of electrons which then move onto needle and mount leading to repulsion.

The following example (Table 2) gives an impression about how the codes are applied to the minutes (abbreviation given in Table 1). The students are given a task rather similar to the example given in Figure 1.[1] They first try out different material which is coded as *Experiment* (explorative). Further on, the students discuss that the card tells them not to touch the electroscope-plate, that is, they verbally focus on an aspect of the task that is important from their point of view (intuitive, *Statement-based*). For their experiments, the students observe that the needle deflects differently (intuitive, *Attribution*), which is further on based on the general idea that the amount of rubbing plays a central role (explicit, *Generalisation*). David then describes what he saw (explorative, *Mental Experiment*) and attributes his idea to the concrete case of an air balloon (intuitive, *Attribution*). In the next task, David starts by remembering the experiments they had just carried out (explorative, *Mental Experiment*) before he explicitly explains how the amount of rubbing and the deflection are connected (explicit, *Explanation*). This example demonstrates that even for the relatively simply connection between charging (rubbing) a material and the deflection of the electroscope's needle the students (here grade 8) need several experiments, (mental) repetition, and attribution of words before they are able to give an explicit explanation – which is based on the connection of two (simple) concepts – of what they were observing.

Table 2. Example of a Minute and Ascribed Codes

Task 3.1:	**Hold rubbed material above the electroscope plate. Do not touch the plate with the material. What do you observe?**
	Students hold different material above the electroscope-plate. [all ET]
	Students discuss that the plate should not be touched with the material. [SB]
	Students find different deflection. [AT]
David:	It does only depend on the rubbing. How heavily one is rubbing and an air balloon cannot be rubbed heavily. [GE]
David:	I always saw the same deflection. [ME]
David:	With the air balloon, the deflection was not very big because the balloon wasn't rubbed heavily. [AT]
	Students fix the results.
Task 3.2:	**What do you observe if objects rubbed differently are used?**
David:	I've seen different deflection. [ME]
David:	The more you rub the more the needle deflects, the less you rub the less the needle deflects. [EX]

Note. Descriptions and the student's comments have been shortened.

Even though the main aim of the research was to set up a coding system which may shed new light onto processes of conceptual development, some results indicate patterns that need to be addressed in further research.[2] The analyses completed so far on about 2.000 events for the investigated high school groups indicate that for both cohorts explicit conceptualisations occurred in less than 10% of the coded events whereas in more than 50% an explorative approach was ascribed. Explorations were not only used to create an idea about particular phenomena or objects, they also often followed intuitive-based assumptions ("let's try…") and were carried out whenever students' intuitive or explicit rule-based understanding was not successful, for instance, did not match their

[1] Card 3.1 serves as a start into the third session and is aimed to provide both a repetition and some expansion of the end of the last session.

[2] Also, the observers' reliability has not yet been tested systematically. Tests on a few random samples indicate a kappa of more than 0.7.

observations or different arguments were developed. Statements that were explicitly based on conceptual knowledge mainly emerged following the completion of tasks, that is, have the status of explanations rather than hypotheses (see David in Table 2). The instructions based on conceptual knowledge were used only once students had already reached a theoretical level on their own. However, they only used the parts of the instruction-cards which referred to the content that they had already developed by themselves.

Empirical Examples and Discussion

Application of the Categories

Currently, the coding system has been improved according to new data gathered in a project on students' argumentation in physics and their learning of physics. However, the system may show its principal validity when being applied to other sets of data that are not (implicitly) gathered with a specific point of view on students' learning and their conceptual change. Therefore, the main categories of the system were used to investigate some transcripts given in the literature on students' learning of science. The next two examples demonstrate briefly how the authors of the studies describe their excerpts and how their description relates to the approach used in this paper.

Example 1: In their work on young children's' conceptual development over several years, Tytler and Petersson trace children' understanding and reasoning of scientific phenomena using one interview per year and child (e.g., Tytler & Petersson, 2003; Tytler & Petersson, 2003). For Jeremy, grade prep (about 5 years old), the following dialogue on how whirlybirds fly is given (coding for Jeremy added in [ ]):

J: *I have an idea, why don't we try it with this one? [explorative]*
Int: *What small and big?*
J: *Yeah, small and big (he predicts the big one will be slower, and tries) [explorative or intuitive]*
Int: *Oh yes, you were right. Can you come and tell me how this works? How does one of these work?*
J: *Um, because it's got longer fins and then it's got longer air and it can catch lots of air, and this one's only got little fins and it can't catch much air, and this can catch lots and lots and lots and lots and lots of air. [intuitive]*
(Tytler & Petersson, 2003, p. 16)

In their description of Jeremy's approach, the authors ascribe a level 3 which indicates that "Children carry out focused observations or interventions which involve trying out an idea, or following up a prediction with some conceptual basis. Explorations have a recognisable hypothesis driving them." (Tytler & Petersson, 2003, p. 28). Even though the authors describe Jeremy's approach having at least some theoretical basis, the theory is not given explicitly in the excerpt but an intuitive understanding of the rules that make different whirlybirds fly is recognizable. (From the introducing description of the excerpt it can be concluded that Jeremy has already had some experiences with whirlybirds beforehand of the excerpt.) From a first order perspective (e.g., Marton & Booth, 1997), research might infer the theory that could be used to derive Jeremy's arguments. However, from a second order point of view, there is no indication that Jeremy arrived at his idea from an explicit theoretical understanding of air resistance or similar aspects.

Example 2: The SEPIA (Science Education through Portfolio) project aimed to integrate curriculum, instruction, and assessment practices at the classroom level (Erduran, 2003). Within the project, a curriculum about acids and bases was developed and evaluated through audio recording of grade 7 students (about 13 years old). The verbal data were transcribed and then the teacher-student interaction was studied in detail.

T: *Ok. Say bromothymol blue. Now you've got to give me some reasons why you choose that. Bromothymol blue. Why did you like that?*
P: *Because it's like, I like when you put two drops of it, it like changes to a different colour. [explorative]*
T: *Different colour change. And what I heard you say? I heard you say different colours. You mean different whether it was an acid or whether it was a base. [explicit]*

For this excerpt, Erduran concludes that the mismatch between the pupil's and the teacher's understanding is a result of a student reporting a particular observation which is then interpreted by the teacher as "referring to a generality or rule about colour change and acidity-alkalinity" (Erduran, 2003, p. 82). Rather than arguing with a conceptual basis, the pupil describes an observation whereas the teacher focuses on a conceptual-based explanation.

Both examples demonstrate that in principle the categories can be applied to students' conceptual development. They also show that different researchers seem to have similar descriptions of ongoing teaching and learning processes.

Discussion of the Categories

For our data as well as for some examples presented in the literature, the coding system has shown to be valuable. However, it should be noted explicitly, that our data refer to learners (novices) and not to experts. Therefore, the coding system may look somewhat different for experts as we would expect that, for instance, experts' activities may show an intuitive understanding as well. That is, experts may carry out an activity at an intuitive rule-based level which is not yet included in the system.

So far, the categories and codes presented were extracted from both theoretical considerations and a (relatively small) empirical basis. However, some literature on human learning and scientists' developing new theoretical accounts for describing the physical world show strong similarities to the system developed. Deacon (1997) describes how human language has developed and is used to describe and theorize phenomena of the physical and mental world. He argues that – in phylo- and ontogenesis – language and signs are manipulated (in an unsystematic manner). Deacon describes this first step towards the development of an expanded usage of language as *iconic*. Further on, language serves as a label for situations and objects; it has an *indexical function*. Even though there might be some overlap between iconic and indexical usage of language within the explorative area of the categories presented, parallels between iconic-explorative and indexical-intuitive are obvious. Finally, language is treated in a *symbolic* manner, that is, words and signs comprise classes of objects and are, therefore, explicitly used to express general properties and principles.

Steinle's (2002) research about the historical development of physics concepts results in a very similar description of how scientists make use of experiments to generate theories about the physical world. In one of his recent articles, Steinle introduces the notion of "exploratory experiment" tracing back how scientists used their prior experiences and (intuitive rule-based) ideas to explore phenomena and construct physics concepts (Steinle, 2002). Other than presented with our data, their prior experiences enabled scientists to produce a systematic variation of experimental parameters in order to explore which parameters have an effect and which have not. Typically, students of lower and upper secondary lack in content specific (and/or relevant) experiences so that their exploration often starts in an unsystematic manner. Or – conversely – the systematic variation, that is, the control of parameters, must be introduced and promoted by the instruction.

More interestingly, Steinle points in his article to a distinction we have also found in our (and other) data but not yet included in the system of categories. In the early stages of concept formation, scientists were typically not interested in, sometimes even not aware of, model-based reasoning. "Dufay was definitely not interested in microscopic theories about the 'hidden nature' of electricity (though he was well aware of the long history of speculations on that question), but rather intended to establish regularities on the level of phenomena and experiments, in a field that he found in an incoherent and unstable state." (Steinle, 2002, p. 418). Further on, Steinle argues „Closely connected, there is the central goal of formulating empirical regularities about […] dependencies and correlations. Typically they have the form of 'if-then' propositions, where both the if- and the then-clauses refer to an empirical level." (Steinle, 2002, p. 419). Also for students in physics, we found that they intuitively develop and then explicitly establish those concepts and conceptual connections that they can infer from their experiences. This is what we would call *phenomenon-based concepts*.

In Table 2, David ended with an explanation that provided a general connection between an activity (rubbing) and related observations (the deflection of the needle). Jeremy in Example 1 describes how the air, though not directly visible but sensible, relates to the size of whirlybirds. Investigating students' commonsense ideas in detail may also reveal that most of these ideas are extracted from everyday experiences ("explorations"). For instance, "You need a steady force to sustain a steady motion" or "Heavier objects fall faster" can be described as such phenomenon-based concepts. Phenomenon-based concepts are, therefore, the result of (intensive) experiences, may it be everyday experiences or experiences within schooling situations. diSessa's p-prims can be considered similar to phenomenon-based concepts as (most) p-prims refer to rules or principles but seem to have a strong empirical basis (e.g., diSessa, 1993; diSessa, 2002). However, it should be noted that, from a physicist's point of view, phenomenon-based concepts provide systematic descriptions rather than physics explanations. So, teachers and researchers may argue that there is almost no value in phenomenon-based concepts as they are not at the "core" of physics as a discipline. In contrast, issues raised here provide strong arguments about the importance of such phenomenon-based concepts for both, the progress of the discipline and the progress in students' understanding. It is then well established phenomenon-based knowledge, reassured and revised via repeated and varying explorations that provides the basis for the need of, the search for, and the understanding of *model-based concepts* and their interrelationships. It is the model-based concepts that contain explanations of physics phenomena. Model-based concepts cannot be inferred from experiences directly and are, therefore, "discovered" relatively late in both, scientific development and individual learning. These assumption concur with Lawson's framework which comprises a five level description of students' increasing competencies using if-then-patterns to reason about content (Lawson, 2003). In his model, it is only stage 5 ("theoretical stage") which relates to model-based reasoning. For that stage, Lawson argues that it is reached in late adolescence and early adulthood. From our empirical results and from Steinle's (2002) description I would rather point out that it is not the age but the familiarity with content that enables learners to reach a model-based understanding. Thus, it is not only in physics research but also in students' learning that model-based concepts require many experiences and are, therefore, established relatively late in the process.

Summary and Implications

"Researchers in science education and cognitive science seem to agree that naïve physics exerts a great deal of influence on the way new information is understood and science concepts are acquired, but disagree on how to characterize the exact nature of naïve physics." (Vosniadou, 2002, p. 61). In this paper, an attempt was made to classify students' knowledge with respect to its conceptual structure. Whenever students describe a phenomenon they have encountered or label a specific situation (maybe by using physics expressions) it was assumed that such kind of knowledge cannot be considered "automatically" as conceptual (even though students may be able to demonstrate an explicit conceptual understanding when being asked). Only knowledge which explicitly comprises (physics) principles, laws, rules, or theory should be considered conceptual. Furthermore, it was argued that explicit concepts can be based upon own (mental) experiences (phenomenon-based concepts) or are a result of theorizing (model-based concepts).

From our process-data we have strong evidence that, indeed, conceptual change is a gradual and slow process, occurring in circular rather than in linear modes. Two different types of changes were described:

(A) A development from a non-conceptual (explorative) approach to a conceptual approach requiring an intuitive understanding in-between. Within such a change, students develop from grappling (a high number of) similar situations or objects to an integrated perspective in which they can explicitly abstract from particular features of these situations or objects. This result concurs with results of research on differences between novices and experts. Whereas experts are able to solve problems on the basis of physics laws and theories novices tend to focus on surface characteristics without an understanding of the conceptual basis (e.g., Chi, Glaser, & Farr, 1988).

(B) A development from phenomenon-based concepts to model-based concepts. Students (and researchers) seem to discover those concepts first that can be inferred directly from distinctions and classifications of their experiences (everyday, in school, in a laboratory). Such concepts have the status of generalisations and do not provide explanations of the phenomena they comprise. Concepts such as “objects fall down when not supported” can be grasped easily (in early childhood) whereas concepts such as “gravity is a force between two objects” require an abstraction from several (and varying) concrete (mental) experiences with different objects and their attraction. Thus, one model-based concept can comprise several phenomenon-based concepts. Or, conversely, students need to develop several phenomenon-based concepts before they are able to construct the associated model-based concept.

Obviously, such a description of conceptual change seems to disregard the contents of the concepts themselves. It should be stressed that no decision of a specific approach or conceptual quality can be made without an explicit focus on the content of the knowledge which is presented by students. Other than with descriptions focusing on the content solely (A) and (B) aim to provide a generalised framework on concepts and conceptual change which can be applied to different topics. As such, the framework is phenomenon-based and not model-based!

Further research into this area not only needs to create and validate model-based concepts accounting for the assumptions and results given in this paper, it also needs to clarify better the different qualities that concepts at all stages of the development can have. This would include more content oriented analyses of students’ thematic focus, the way in which students integrate different content elements within one concept or how students construct concepts in which variables dynamically interrelate. Also, the amount of time students need to develop a concept of a specific quality can indicate differences in their understanding (more details in von Aufschnaiter, accepted; von Aufschnaiter & von Aufschnaiter, 2003).

All assumptions and empirical results given should be seen as work in progress rather than as a well established framework. However, cross-references to other statements given in the literature on students’ learning of science strengthen my perspective on conceptual change and may, therefore, provide enough grounds to formulate some educational implications.

Educational Implications

Theoretical framework and empirical evidence on the typical learning development (in physics) would enhance our ability to construct instruction which offers at any stage of the learning process the appropriate level of learning demand (e.g., Vosniadou & Ioannides, 1998; Leach & Scott, 2002). For formal instruction, it is assumed that students’ conceptual knowledge needs to be taken into account: “Teachers need to be informed about how students see the physical world and learn to take their points of view into consideration when they design instruction." (Vosniadou et al., 2001, p. 392). Nowadays, a large body of research has focused on students' concepts and several references provide lists of students' understanding in specific domains (e.g., Driver, Squires, Rushworth, & Wood-Robinson, 1994; Duit, 2004). Although these lists give valuable insights into students' ideas, they are also problematic for at least two reasons. Such kinds of lists turn the readers' (teachers') focus towards concepts instead of experiences. Research reported in this paper indicates that students rarely construct explicit concepts and if they do so, the concepts are often phenomenon-based. On the other hand, at least some of the questions aimed to measure students' understanding explicitly focus on models, for instance, by asking what happens within an electric circuit. Here, students are "forced" to make a "guess" which, in turn, may not say a lot about students' understanding as students' may not yet have arrived at conceptual level, let alone a model-based understanding. However, several concepts documented can be used to infer from these concepts students' underlying experiences. In terms of conceptual development it is the experiences that enable and limit students' understanding at the same time. For instance, we might then understand better, why students consider mass for floating and sinking – it is the mass that typically makes the effect in the world – or why students argue that shadows are objects on their own (having not yet experienced the connection between light and shadow). Also, we can understand why the distinction between energy and force is so difficult to students, as both concepts are model-based. Instead of focusing on concepts, the focus on experiences would enable a teacher to understand better which experiences need to be differentiated further and where it is appropriate to introduce new experiences.

The other reason why lists of students' concepts are problematic is that they do not say anything about appropriate instruction. Measuring a "gap" between what students know and what they are ought to know gives almost no hints about how to "close" the gap. Research seems to agree about the need to define appropriate level of demands, so that students can restructure their knowledge and will not just try to learn the new information by heart or "ignore" what is presented to them. If it is students' missing and existing experiences that are important for their conceptual understanding, instruction systematically needs to focus on experiences. Although experiments certainly play an important role in formal instruction, they are often considered and used to demonstrate a specific concept (that is, using single experiments that show best what is needed to be seen). Experiments are assumed to generate cognitive conflict or at least dissatisfaction with existing concepts (e.g., Posner, Strike, Hewson, & Gertzog, 1982; Strike & Posner, 1992). However, if students do not yet have a (model-based) concept dealing with the presented content, they are not very likely to "understand" what is to be conflicted and what kind of concept the experiment is about to demonstrate. As students are able to figure out rules from their teacher's behaviour they are much more likely to learn (create a phenomenon-based concept) when and what to say so that the teacher is "pleased". Such behaviour, in turn, often results in knowledge that appears to an observer incomplete, as a synthetic model, or a misconception. It may be our culture to use experiments (or pictures or movies) that hinders rather then enables students to learn scientific concepts: experiments play an important role in connecting theory to praxis but are rarely considered as means by which students *discover* new knowledge by themselves.

The (main) categories on conceptual development (Table 1) and observed processes of change ((A) and (B) above) may serve as guidelines on how to structure instruction so that it offers an appropriate level of demand which matches students' learning process. Students need to explore phenomena systematically with relatively great extend so that they can develop an intuitive understanding of commonalities and differences before they are able to construct and understand phenomenon-based concepts explicitly. The categories also show that instruction should allow exploration at any further stage of students' conceptual development so that students can re-discover, re-assure, and revise their intuitive and explicit rules. In more detail, it is the series of coherent (mental) exploration of phenomena with respect to varying parameters that will support students to develop an intuitive and, later on, explicit phenomenon-based understanding. In that, students' prior experiences need to be differentiated further. For instance, they need to explore systematically the effects that objects of different volume but the same material, of different masses each with the same volume, or of different shapes but made of the same material have on floating and sinking. Further on, students need to be supported to investigate systematically what happens to the water level when objects of different volumes, masses, and material are inserted, and how the water pressure differs depending on the volume that is inserted. Here, new experiences are created which have not yet been in the focus of students' activities. Finally, the mass of the object and the mass of the displaced water can be compared (for such an approach see Möller, Jonen, Hardy, & Stern, 2002). Even though students may not discover the model-based concept of buoyancy, they will develop an intuitive understanding of which objects float and which will not (most adults have such an understanding developed through their experiences) and may also be able to create a phenomenon-based concept about floating and sinking referring to the interrelationship of the mass of the displaced water and the mass of the object.

The instructional approach, very briefly outlined, does not focus (at the beginning of a new content) on scientific concepts explicitly. Instead, it improves, develops, and introduces experiences to students systematically as these are a prerequisite for students to arrive at a model-based understanding. Such an instruction does not focus (at an early stage) on "good" explanations but on "good" discoveries. From our and other data I would conclude that (expanded and differentiated) phenomenon-based concepts are a realistic goal for (lower) secondary physics education. Aiming to improve students' scientific understanding rather than their understanding of what words are most convincing to the teacher, concrete (mental) activities instead of concepts should make up about 80% of classroom activities (including students' debates about what they observe, how their observation relates to other phenomena, completion of worksheets and so on) in secondary schools.

Certainly, seeing students mainly arriving at an intuitive rule-based understanding or an explicit understanding of phenomenon-based concepts may sound trivial and not enough for schooling (at secondary level). However, as Steinle points out, the scientific development of model-based concepts is a very complex and difficult process which required several decades in history. „Most prominently, Ampère himself considered, in all his later reasoning on microscopic circular currents, the concept of a current circuit as an unproblematic foundation. Similar observations hold, finally, for Faraday's 'magnetic curves,' though it took, in that case, several decades until the concept appeared acceptable […]. Nowadays, however, we take it up in school. Since those notions now appear as somewhat natural, the very fact that they have been created out of hard labour easily slips out of view." (Steinle, 2002, p.424).

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