Exploring the development of student teachers' PCK of the multiple meanings of chemistry concepts

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EXPLORING THE DEVELOPMENT OF STUDENT TEACHERS' PCK OF THE MULTIPLE MEANINGS OF CHEMISTRY TOPICS

ABSTRACT. In chemical education, many secondary school students experience difficulties in understanding three mutual related meanings of topics, that is, the macroscopic meaning, the microscopic meaning, and the symbolic meaning. As a consequence, student teachers should be prepared carefully to learn how to teach this difficult issue. This article presents a naturalistic case study of the development of eight student teachers' pedagogical content knowledge (PCK) of the multiple meanings of chemistry topics. The student teachers (all M.Sc.) participated in a teacher education program of which the initial phase focused on learning from teaching instead of learning of teaching. They were asked individually to choose and teach a chemistry curriculum topic with a focus on the macro-micro-symbolic issue. Research data were obtained by interviewing the student teachers individually before and after the lessons. The outcomes indicated a development of student teachers' knowledge of teaching difficulties, for instance, too fast and mainly implicit reasoning between macro- and micro-meaning, and a dominant orientation towards the micro-meaning of topics. A development of knowledge of students' difficulties was also indicated, for instance, difficulties in understanding the macro- and micro-meaning of reaction equations. Implications for the follow-up phases of the program are presented.

KEY WORDS: learning from teaching, macro-micro-symbolic meanings of topics, science teachers' knowledge

An important component of teachers' knowledge base of teaching is often called 'pedagogical content knowledge' (PCK), a term coined by Shulman (1986). To develop PCK, teachers need to gain experiences with respect to teaching particular topics in practice. Also, they need to gain an understanding of students' conceptions and learning difficulties concerning these topics (Lederman, Gess-Newsome & Latz, 1994). However, so far, not much is known from research about the process of PCK development among student teachers. Clearly, understanding of the development of PCK is necessary to design effective teacher education programs. The purpose of the present study was to contribute to this area. This study focused on the development of student teachers' PCK in the context of a one-year post-graduate program aimed at obtaining a qualification for teaching chemistry in upper secondary schools in The Netherlands. All participating student teachers had a master's degree in chemistry.

Another important characteristic of PCK concerns its relation to specific issues or subjects (Shulman, 1986). In the present study, the focus

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was on an important issue in teaching chemistry, that is, the mutual related meanings of chemistry topics in terms of phenomena, particles, and symbolic representations. Little is known about (student) teachers' PCK of this issue, and how it is developed. Below, we first address concisely two important elements of our study, that is, the nature and the development of pedagogical content knowledge, on the one hand, and the issue of multiple meanings of chemistry topics, on the other hand. Next, we report on the empirical part of the research project, followed by discussion and implications.

Nature and Development of Pedagogical Content Knowledge

Elaborating on Shulman's work, various scholars have proposed different conceptualizations of PCK, in terms of the features included or integrated (Grossman, 1990; Marks, 1990). Some describe PCK as a 'mixture' of several types of knowledge needed for teaching, while others explain PCK as the 'synthesis' of all knowledge elements needed in order to be an effective teacher (cf. Cochran, DeRuiter & King, 1993). Magnusson, Krajcik, and Borko (1999) have presented a strong case for the existence of PCK as a separate and unique domain of knowledge. In any case, PCK, referring as it does to particular topics, is distinct from general knowledge of pedagogy, educational purposes, and learner characteristics. Moreover, because PCK is concerned with the *teaching* of particular topics, it may differ considerably from the 'related' subject matter knowledge. However, several authors have pointed out that it is not always possible to make a sharp distinction between PCK and subject matter knowledge (Marks, 1990; Tobin, Tippins & Gallard, 1994). Loughran and co-workers have defined PCK as "the knowledge that a teacher uses to provide teaching situations that help learners make sense of particular science content" (Loughran, Milroy, Berry, Gunstone & Mulhall, 2001, p. 289). These authors argued that investigations of PCK should avoid reducing PCK to a mechanistic, technical description of teaching, learning and content.

Magnusson et al. (1999) conceptualized PCK as consisting of five components: (a) orientations towards science teaching, (b) knowledge of the curriculum, (c) knowledge of science assessment, (d) knowledge of science learners, and (e) knowledge of instructional strategies. In the present study, the focus was on the components (d) and (e), related to specific chemistry topics. Regarding knowledge of science learners, we want to focus specifically on knowledge of students' learning difficulties. Regarding knowledge of instructional strategies, we want to focus on knowledge of teaching difficulties. Both components are intertwined and should be used in a flexible manner: the better teachers understand their students' learning processes within a certain domain, and the more activities they have at their disposal in the same domain, the more effectively they can teach in this domain.

In the literature on PCK, various suggestions can be found to promote the development of student teachers' PCK in the context of teacher education programs. For instance, Magnusson et al. (1999) argued that the development of PCK is a complex process, which is determined, among other things, by the nature of the topic, the context in which the topic is taught, and the way a teacher reflects on teaching experiences. These authors concluded that a teacher education program could never completely address all the components of PCK a teacher needs. Grossman (1990) identified four major sources of PCK development: (a) disciplinary education, naturally, constitutes the basis for subject matter knowledge and, as a consequence, constitutes the basis for knowledge of representations (e.g., analogies and examples) for teaching, (b) observation of classes may, for instance, promote student teachers' knowledge of students' learning difficulties, (c) classroom teaching experiences may, for instance, promote student teachers' knowledge of topic-specific teaching activities, such as demonstrations and investigations, and teaching difficulties, and (d) specific courses or workshops during teacher education have also the potential to affect PCK. It seems that the most important contributions are made by disciplinary education (Sanders, Borko & Lockard, 1993) and classroom teaching experiences (Lederman et al., 1994). However, as there have been few studies on the ways PCK develops over time, the relative impact of each of these four factors is not very clear.

TEACHING THE MULTIPLE MEANINGS OF CHEMISTRY TOPICS

In science education, especially chemical education, most topics can be considered from different perspectives. A well-known categorization of these perspectives is given by Johnstone (1991) who made a distinction between three mutual related perspectives (see Figure 1). First, the macroscopic perspective, that is, meanings of topics are expressed in terms of phenomena, substances, energy, and so on. Second, the microscopic (sometimes called: submicroscopic) perspective, that is, meanings of topics are expressed in terms of molecules, atoms, ions, and so on. Third, the symbolic perspective, that is, meanings of topics are expressed in terms of formulas, equations, ionic drawings, and so on. The present study will deal

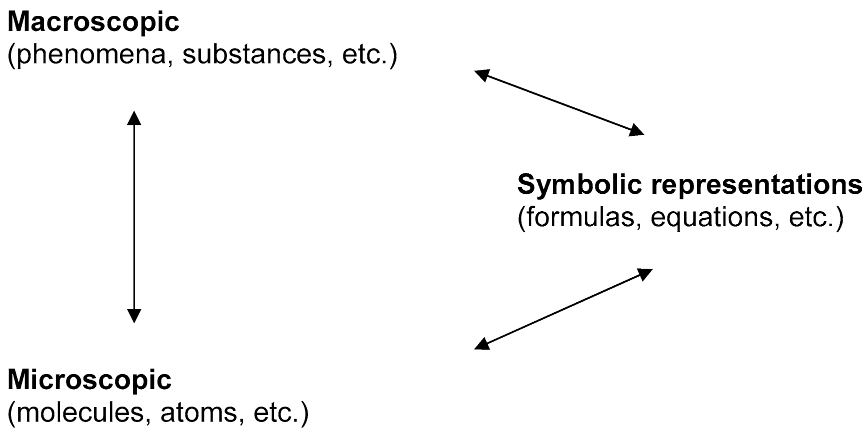

Figure 1. The macro-micro-symbolic triangle of meanings.

with the multiple (macro-, micro-, and symbolic) meanings of topics in the context of chemistry teacher education only.

Secondary chemistry teachers are experienced in going from the macro-meaning to the micro-meaning and back to the macroscopic, using formulas, atomic symbols, and so on. For them, a formula as H_2O refers to the substance of water as well as to a single molecule of water. Their mental switching between macro-aspects and micro-aspects of science curriculum topics is conducted easily and almost automatically (Johnstone, 1993). However, secondary school students often experience difficulties in understanding the multiple meanings of chemistry topics. For example, they have to learn to consider chemical reactions as conversions of substances. But they also have to learn the microscopic meaning in terms of rearrangement of particles, and the symbolic representation in terms of chemical equations (words, iconic drawings, formulas). For them, the conceptual demands of shifting between the three meaning domains can be overwhelming. Their difficulties in understanding macro-micro meanings, for instance, explaining observations of phenomena in terms of interactions between particles, have been reported in several studies (e.g., Benson, Wittrock & Bauer, 1993; Lee, Eichinger, Anderson, Berkheimer & Blakeslee, 1993; Treagust, Chittleborough & Mamiala, 2003). Students also appear to experience difficulties in understanding symbolic representations, for instance, they handle symbols as algebraic entities without clear interpretations from a macro-micro perspective (Ben-Zvi, Eylon & Silberstein, 1988; Friedel & Maloney, 1992).

As learning to link phenomena with particles and symbolic representations constitutes one of the most important objectives of science education, student chemistry teachers need to develop knowledge of teaching the macro-micro-symbolic issue. We assume that the student teachers, being educated as chemists, have developed a habit of discussing multiple meanings in a flexible and implicit manner, thus creating confusion among their students. As a consequence, student teachers will encounter difficulties when teaching topics at a macro-micro-symbolic interface.

In the context of a teacher education program, the present study was guided by the following research question: what development of the student teachers' PCK can be identified concerning the issue of the macro-micro-symbolic meanings of chemistry topics? In this question, PCK refers to knowledge of teaching difficulties and student-learning difficulties.

RESEARCH METHOD

Context and Participants

The present study was situated in the context of a one-year post-graduate teacher education program, qualifying participants for the teaching of chemistry at pre-university level (cf. grades 10–12 of secondary education). Before entering this program, the participants had obtained a Master's degree in chemistry. In the context of the program, the student teachers taught at practice schools (teaching about five to ten lessons per week). They also took part in institutional meetings and workshops (two afternoons per week, on average). Regarding learning how to teach the mutual related meanings of chemistry topics, the initial phase of the teacher education program focused on offering opportunities for *learning from teaching* instead of *leaning of teaching*. The latter approach assumes that student teachers learn in a mainly passive way how to teach, whereas learning *from* teaching means that student teachers learn in an active way, involving real practice situations, to make their learning more meaningful to themselves (cf. Lampert & Loewenberg, 1998). Our choice was to develop their PCK of the issue under consideration by asking them to design lesson plans, to execute the plans in their practice schools, and to reflect on their teaching practice.

The subjects in the study were eight (five females and three males) student teachers in chemistry; all had a Master's degree in chemistry. The participants (referred to below as ST 1–8) entered the research project at the beginning of the third month of their program. During the preceding months, no specific attention was given to the meaning or use of the macro-micro-symbolic interface. At the start of the project, the student teachers were asked individually to choose a forthcoming topic from the chemistry curriculum with an emphasis on the relationship between phenomena, particles, and reaction equations.

Five participants (ST 1–5) chose dissolving and precipitating processes of salts in water as the topic they would teach to students of grade 10 (age 15–16). Their aim was to relate precipitation phenomena (when particular solutions of inorganic salts are poured together; *macro*) to interpretations in terms of the dynamics of involved ions (*micro*), and expressed as precipitation reaction equations (*symbolic*). Three participants (ST 6–8) chose balancing simple reaction equations as the topic they would teach to students of grade 9 (age 14–15). The aim was to relate the law of mass conservation for chemical reactions (main example: combustion reactions; *macro*) to interpretations in terms of the conservation of atoms of the same kind (*micro*), and expressed as balanced reaction equations (*symbolic*). All student teachers taught their topic in his/her practice teaching school, using the current textbooks.

Data Collection

In the context of the study, the student teachers were interviewed individually by one of the authors before and after the lessons (four lessons about dissolving and precipitation reactions; two lessons about balancing reaction equations). During the pre-lesson interview, they were asked to show and explain their lesson plans. They were also asked to express their expectations regarding the students' conceptual difficulties as well as their expectations regarding their own difficulties in teaching the topic. During the post-lesson interviews, they were invited to report and reflect on their teaching experiences, especially with respect to teaching and learning difficulties. All interviews were conducted in a semi-structured way that allowed the student teachers to tell their own expectations and reflections, respectively, and to introduce issues the interviewer had not thought of. All the interviews were audio recorded. The lessons under consideration were also audio recorded (by the student teachers themselves).

The interviews and classroom discussions were transcribed verbatim. The interview transcriptions served as the core data source for the study. As we were interested in the student teachers' knowledge, rather than in their classroom behavior, the recordings of the lessons were used as additional data, mainly serving to improve our understanding of the context in which the student teachers had taught their lessons. In addition, our analysis of the relevant chapters of the chemistry textbooks provided extra contextual information.

Data Analysis

The research data were analyzed by a step-by-step procedure. First, each author of this paper analyzed the pre- and post-lesson interview transcriptions of the individual student teachers in an iterative way. The following main categories were used for this analysis: teaching difficulties, and student-learning difficulties. Subsequently, within each category, statements were classified into subcategories: four concerning teaching difficulties and two concerning student-learning difficulties. In the next phase, analysis results of the individuals were compared to identify common difficulties. In this phase, researcher triangulation (Janesick, 1994) was applied by comparing and discussing the interpretations by the first and second author. The validation of these interpretations was promoted by applying the constant comparative method (Denzin, 1994). This involved the comparison of the analysis of the interview transcriptions with other sources, viz (a) the transcriptions of the classroom discussions between students and the student teachers, and (b) additional data, especially chemistry textbooks, to trace the possible origins of the student teachers' statements.

FINDINGS

In general, the results of the pre-lesson interviews indicated that three student teachers (ST 3, 6, 8) reported to expect teaching and/or student-learning difficulties they might encounter, but they expressed these difficulties in rather vague and short statements. The other five student teachers indicated that they hardly expect significant difficulties. The results of the post-lesson interviews indicated that the student teachers with expectations about difficulties not only elaborated on these difficulties, but they also added new teaching and/or student-learning difficulties. Moreover, the other half of the student teachers also reported teaching and/or student-learning difficulties. The post-lesson difficulties were usually expressed in a rather extensive and detailed way. A summarized overview of the results is given in Table I. A specification of the findings is given below.

Knowledge of Teaching Difficulties

Regarding teaching difficulties, four subcategories could be distinguished (Table I). Three of them could be identified after teaching only. These categories will be reported first, followed by the fourth one.

1. Too Fast Reasoning between Macro- and Micro-Meanings. All student teachers expressed to have experienced teaching difficulties in terms of

TABLE I

Teaching and student-learning difficulties, reported by the student teachers

Categories of difficulties	Student teachers (STs; $n = 8$) reporting difficulties	
	Before teaching	After teaching
Teaching difficulty		
* How to prevent too fast reasoning between macro- and micro-meanings	no STs	ST 1, 2, 3, 4, 5, 6, 7, 8
* How to prevent a dominant orientation towards the micro-meaning of topics	no STs	ST 1, 2, 3, 4, 5, 6
* How to prevent mixing together macro- and micro-meanings in a confusing way	no STs	ST 1, 2, 3, 5, 7, 8
* How to handle textbook prescriptions for noting symbolic representations	ST 8	ST 1, 5, 6, 7, 8
Student-learning difficulty		
* Understanding the macro- and micro-meaning of formulas	ST 6, 8	ST 1, 3, 5, 6, 8
* Understanding the macro- and micro-meaning of reaction equations	ST 3, 6, 8	ST 1, 3, 5, 6, 8

their too fast reasoning between the macro- and micro-meaning of topics. They acknowledged that their reasoning was not only fast but also mainly unconsciously. An illustrative statement is (referring to the case of a precipitation reaction by pouring an excess of a nickel salt solution to a colorless solution of another salt):

I became much more aware that you switch very fast from one level to another level. You are not conscious of it. So, then, . . . you change very fast between the fact of having a green solution after pouring together, and, so, there must be nickel ions in the solution. Students have a lot of difficulties in transferring and to decide when something is at macro-level and when something is at micro-level, we do not have that. [ST 3; post-teaching interview]

The student teachers had noticed that their students could often not follow their quick mental jumps from one perspective of meaning to another perspective of meaning. They wondered how to prevent their way of reasoning between macro- and micro-meanings.

2. Dominant Orientation towards Micro-Meanings. Six student teachers (ST 1–6) expressed teaching difficulties in terms of their dominant orientation towards the micro-meaning of topics. They indicated that they were inclined to reason spontaneously in terms of particles without any explicit reference to relevant observations of phenomena. This strong orientation towards the micro-meanings of reactions mainly occurred when they carried out experiments in the classroom. An illustrative statement is (referring to the case of the formation of a salt precipitate):

> Often (. . .) I start to talk about particles immediately instead of giving them the opportunity to observe first. For instance, saying, what do you see, two clear solutions, a solid substance appears, and, then, going to the interpretations. I am inclined to dive to the particles immediately (. . .). Yes, saying, what happened, the copper ions go to the hydroxide ions and together they form a precipitate, instead of observing the phenomena first, and, from there go to the particles. When I see that the precipitate becomes white, then, immediately, I think, a precipitate is formed from two ions. I do it automatically, but students do not. For them, it is not clear. [ST 2; post-teaching interview]

The student teachers had experienced that this way of teaching caused a lot of students to fail to understand new concepts and rules. They wondered how to prevent their dominant orientation towards the micro-meaning of topics.

3. Mixing together Macro-Meanings and Micro-Meanings. Six student teachers (ST 1–3, ST 5, 7, 8) expressed teaching difficulties in terms of their confusing way of mixing together the macro-meaning and the micro-meaning of topics. They indicated that they did not make a clear distinction between these meanings, mainly by talking imprecisely. For instance, one of the student teachers reported (in the case of balancing the reaction equation for the decomposition of water):

> Several times, I used expressions like "the amount of hydrogen should be the same before and after the reaction." I would focus on the micro-meaning of the decomposition only, to the amount of hydrogen atoms before and after. But, by saying it in the way I did, my students became confused, because they start to wonder whether hydrogen gas exists in the liquid of water, so, a macro-meaning. I did not talk very carefully. Using terms as "the same number of hydrogen atoms before and after" should have been better. [ST 4; post-teaching interview]

The student teachers had experienced that their students became confused by this way of teaching, especially their rather sloppy terminology, and, for that reason, encountered conceptual difficulties. They wondered how to prevent their tendency to mixing together macro- and micro-meanings in a confusing way.

4. Handling prescriptions for noting symbolic representations. A majority of the student teachers (ST 1, ST 5–8) wondered how to handle textbook prescriptions for noting symbolic representations (formulas, reaction equations) in a proper way. One of them (ST 8) had also expressed this kind of teaching difficulty before the lessons, but in vague terms only. For the topic of dissolving and precipitation reactions, the student teachers (ST 1, 5) indicated teaching difficulties regarding textbooks prescriptions for writing down formulas of salts. They reported that the textbooks contain salt formulas that are noted as, for instance, $Na^+Cl^-(s)$ and $Pb^{2+}(I^-)_2(s)$. According to them, these kinds of formulas appeared to be confusing for students because of the presence of signs of charge. A clarifying statement is:

> Confusing, because, in that case, you have charged things in a solid substance, and I actually try to teach them that a solid substance consists of charged things but the whole is neutral, otherwise, it would not be a solid but an ion. But it was not easy for me to convince them. [ST 1; post-teaching interview]

Both student teachers (ST 1, 5) wondered how they could handle these textbook prescriptions for supporting student-learning. The other three student teachers (ST 6–8) were dissatisfied with several textbook prescriptions for noting reaction equations, because, according to them, these prescriptions were not very appropriate. For example, they were not satisfied with the textbook heuristic for balancing reaction equations following a particular step-by-step procedure. They wondered how to handle these prescriptions, because their students preferred to use their own (deviant, but successful) heuristics.

Knowledge of Student-Learning Difficulties

Regarding student-learning difficulties, two categories could be distinguished (Table I). Both could be indicated before and after teaching. They will be described concisely below.

1. Misunderstanding Meanings of Formulas. After teaching, five student teachers (ST 1, 3, 5, 6, 8) reported students' difficulties in understanding the macro- and micro-meaning of formulas. Two of them (ST 6, 8) had also reported this kind of difficulty before teaching, but in very general terms only. After the lessons, some of the five student teachers (ST 1, 3, 5), who had taught dissolving and precipitating processes, reported students' difficulties in understanding the difference between a notation referring to a macro-meaning and a notation referring to a micro-meaning. As a student teacher reported for the case of salt solutions:

They do not make a distinction between a notation like NaCl(aq), which refers to an aqueous solution of sodium chloride, so, macro, and a notation like $Na^+(aq) + Cl^-(aq)$, which refers to particles in an aqueous solution of sodium chloride, so, micro. For me, there are differences in meaning, but for them, no. [ST 1; post-teaching interview]

After the lessons, the other student teachers (ST 6, 8), who had taught balancing reaction equations, reported students' difficulties in understanding formulas used to refer to non-decomposable substances consisting of multi-atomic molecules. According to both student teachers, a substance like oxygen should be represented by the formula O_2, whereas students think that this should be the formula O. Such students' conceptions may cause learning difficulties. One of the student teachers expressed this as follows:

A student said: water contains dissolved oxygen. Yes, he said, because fishes take oxygen from the water. Yes, he said, H_2O is the formula for water, and oxygen is O. So, it is there. Well, I am afraid, they do not think beyond. [ST 6; post-teaching interview]

2. Misunderstanding Meanings of Reaction Equations. After teaching, five student teachers (ST 1, 3, 5, 6, 8) reported students' difficulties in understanding the macro- and micro-meaning of reaction equations. Three of them (ST 3, 6, 8) had also reported this kind of student difficulty before teaching, but in vague terms only. After the lessons, some of the five student teachers (ST 1, 3, 5) reported students' difficulties in understanding writing and interpreting dissolving and precipitation equations, especially concerning the presence or absence of signs of charges in the equations. As an example, they mentioned equations referring to the dissolving of precipitation of salts in water. According to the student teachers, dissolving equations should be noted as, for instance, $NaCl(s) \rightarrow Na^+(aq) + Cl^-(aq)$, just as precipitation equations should be noted as, for instance, $Pb^{2+}(aq) + 2\ I^-(aq) \rightarrow PbI_2(s)$. However, the student teachers reported that some students wondered why they should actually write down signs of charge in equations for dissolving processes, because the formed salt solution is as neutral as the initial salt. For precipitation processes, other students wondered why it is not allowed to write down signs of charge in the formula of the salt precipitate, because the product is formed from ions. An illustrative student teacher statement is:

They are confused. Most of the students knew that a solution itself is obviously not charged. If you put your finger in it, nothing happens. If you touch a salt in a normal way, nothing happens too. But when should you add pluses and minuses? That was strange ... why should you write down $Pb^{2+}(aq)$, why add that two plus? [ST 5; post-teaching interview]

By the way, the three student teachers (ST 1, 3, 5) also reported that student prefer to write down signs of charge in salt formulas in the context of precipitation equations only. Outside this context, the students prefer to write down salt formulas without these signs. According to the student teachers, this variety of preference indicates the impact of context on students' conceptions of the macro-micro issue.

The other two student teachers (ST 6, 8), who had taught balancing reaction equations, reported that the balancing activity stimulated students to interpret reaction equations mainly in terms of particle entities. For example, in the case of the decomposition of liquid water by electrolysis (demonstrated in the classroom), the students encountered difficulties in interpreting the reaction equation: $2\ H_2O\ (l) \rightarrow 2\ H_2\ (g) + O_2\ (g)$. The student teachers reported that most of the students understood the link between the (2 : 1) ratio of observed volumes of both gases (macro) and the (2 : 1) ratio of the number of accompanying molecules (micro), but they did not understand the macro-meaning of the expression '$2\ H_2O\ (l)$' in the equation.

DISCUSSION AND IMPLICATIONS

The findings of this study show a number of interesting aspects of the development of the student teachers' PCK with respect to their knowledge of difficulties in teaching and learning the multiple meanings of chemistry topics.

Regarding teaching difficulties, the results indicate that this kind of difficulties was hardly reported before the lessons. After teaching, much more difficulties were reported. The major kind of difficulties regards the student teachers' personal way of teaching the macro-micro issue, viz. too fast zigzag reasoning between meanings, a dominant orientation towards micro-meanings, and a confusing way of mixing together the macro-meaning and the micro-meaning of topics. The development of their knowledge of these teaching difficulties reflects an emerging awareness of how they handle the macro-micro issue by themselves. The absence of this awareness before teaching can be explained by looking at the student teachers' subject matter knowledge. To them, switching between meanings from the macro-domain, the micro-domain, and the symbolic domain has become second nature, just as reasoning in terms of particles, and mixing together macro- and micro-meanings. Their knowledge and skills with respect to the macro-micro issue have accumulated during a long period of learning (school) chemistry. To be conscious of novices' conceptions is not something that comes easily to experts (De Jong, Acampo & Verdonk, 1995).

Another kind of teaching difficulties regards how to handle textbook prescriptions for noting symbolic representations like formulas and reaction equations. This is interesting, because, as Yager (1983) and Yore (1991) have pointed out, science (student) teachers usually see textbooks as very important sources of information, which have a strong influence on shaping their teaching. Nevertheless, as Abraham, Grzybowski and Renner (1992) have indicated, textbooks fail to contribute to students' understanding of basic chemical concepts as conversion of substances (macro) and conservation of atoms at reactions (micro). The results of our study show that, before teaching, nearly all student teachers did not really expect teaching and student-learning difficulties from the textbook. However, after teaching, a majority of the student teachers became aware of several specific shortcomings in the textbooks. The student teachers' initial positive ideas about the quality of the chemistry textbooks can be explained by the hindering effect of their own subject matter expertise, that is, they are not aware anymore of possible difficulties in understanding something that is very clear to themselves.

Regarding student-learning difficulties, the results indicated difficulties in understanding the multiple (macro- and micro-) meaning of formulas as well as reaction equations. Before teaching, these difficulties were reported by a minority of the student teachers only. This may be explained as follows. During the two months before the research project, all student teachers had already taught some other chemistry topics, partly to other classes, and a minority of them may already have observed some students' difficulties in understanding formulas and equations. Nevertheless, after teaching, student-learning difficulties were reported by a majority of the student teachers.

From the present study, some implications for the follow-up phases of the teacher education program can be given. We would indicate that the results of the present study reflect the impact of teaching practice on the development of student teachers' practical knowledge base (cf. Lederman et al., 1994). Moreover, the opportunity for *learning from teaching*, offered in the initial phase of the program, appeared to be an effective way for evoking the student teachers' awareness of specific teaching difficulties as well as student-learning difficulties, even after a rather small number of lessons in a particular topic. This awareness appeared to act as an initiator for motivating the student teachers to look for possible adequate responses to the difficulties they have encountered or observed. In the follow-up phases of the program, the use of articles from the educational literature in institutional workshops is recommended, providing that the timing and the format of these sessions enables the student teachers to relate their own experiences and beliefs to the content of such articles. Regarding the issue of macro-micro-symbolic meanings, a rich collection of useful literature exists, documenting, for instance, specific students' preconceptions, the effects of certain instructional strategies, etc. (cf. Harrison & Treagust, 2002; Johnson, 2002). A database of students' conceptual and reasoning difficulties (CARD) can be found on the website: www.card.unp.ac.za. Studying relevant literature can stimulate student teachers to re-reflect on their previous teaching experiences and observations, and to analyse relevant sections from their chemistry textbooks. In this way, the student teachers can use their new acquired PCK to develop newly intentions for the teaching of other topics that include the macro-micro-symbolic issue.

In sum, it is important that student teachers get the opportunity to link their authentic teaching experiences with analyses of relevant articles, for instance, about students' preconceptions and ways of reasoning in a specific domain (see also Geddis, 1993). In further research, this link should be investigated in more detail for a better insight in the development of student teachers' PCK. It will be clear that his suggestion, just as the above recommendations, can also be applied to other issues than the macro-micro-symbolic issue.

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