Educational research

Results of an interview study as basis for the development of stepped supporting tools for stoichiometric problems

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Abstract: In recent years many research studies investigated students' misconceptions in stoichiometry, and problem solving strategies on stoichiometric problems. Additionally, alternative approaches for teaching this issue of chemistry were developed. However, among students and teachers this topic is still regarded as being difficult and unmotivating. Our approach is to combine (qualitative) investigations with the development and evaluation of specific teaching and learning material. To help students working on stoichiometric problems, we developed a set of stepped supporting tools (SST), based on the results of an interview study investigating the phases of the solution processes of German secondary school students (grade 9) on these problems. Resulting from students' difficulties detected in the interviews, which were in good agreement to those described in the literature, four different types of SST were developed, (1) giving general instructions on how to tackle (these) problems, (2) showing the steps of the solution process, (3) advising students how to carry these steps out and finally (4) providing them with a glossary of important terms. The method seems also to be applicable to other topics in chemistry, raising the prospect of a catalogue of SST for other problems, too. [*Chem. Educ. Res. Pract.,* 2007, **8** (1), 13-31]

Key words: stoichiometry, stepped supporting tools, problem solving, misconceptions, problem-centered interviews

Introduction

In research on education in the sciences there seem to be two main ways of working: many research groups focus on investigating certain aspects of science education, trying to give a detailed description of e.g. students' ways of thinking or the pros and cons of a certain teaching method. Other research groups try to develop teaching or learning materials to improve on classroom situations. However, the two aspects of research are seldom linked to each other. Although there are models that try to combine the two sides of the same coin [e.g. 'the model of educational reconstruction' (Duit, et al., 2005) or the model of 'developmental research' (Lijnse, 1995)] the 'investigating researchers' often only provide 'recommendations for teaching' without building on their results to produce teaching modules. Our approach tries to bridge this gap between investigation, development and evaluation. In a pilot project we tried to determine students' problem solving strategies on stoichiometric problems and to link the observed difficulties and underlying misconceptions to the steps of their solution in order to devise 'stepped supporting tools' (SST) for this type of problem. Using SST means that, while working on a (stoichiometric) problem, students can rely on a set of prepared cards, which give them supporting information for the solution of the problem without providing them with the full solution. It is widely agreed that providing every student solving a problem with the specific help he/she needs to overcome obstacles in the process of the solution is a very important factor in teaching. The method of using SST may be one way to approach this goal (cf. ForschergruppeKassel, 2006). To do this properly one has to know two things: (1) the way the student solves certain problems and (2) the problems and misconceptions that may obstruct this process. In recent decades many studies have been conducted to find out about students' misconceptions (cf. Griffiths, 1994; Barker, 2000) and about students' problem solving strategies in chemistry (cf. Gabel and Bunce, 1994). Although these data may be meaningless for any individual pupil, they give a broad database for determining which problems are most common and therefore need special attention.

The main purpose for the use of this kind of SST is not in an introductory stoichiometry course, but rather when stoichiometric problems are given to a class for practice. Within the project our goal is to extend our method to other chemical issues to generate a catalogue of SST for many problems in chemistry. This paper shows the method used to investigate students' strategies and to develop the SST. Another paper showing the specific design of the SST and the first evaluation results is in preparation.

Background

Much research has been done on stoichiometric problems in recent years (for reviews see e.g. Gabel and Bunce, 1994; Griffiths, 1994; Furió, et al., 2002). This is probably due to the fact that stoichiometry is a very basic and fundamental concept in chemistry. For example, students have to switch from thinking about concrete aspects of matter to more abstract thinking concerning aspects of particles, thus, they may enhance their conceptual understanding (cf. BouJaoude and Barakat, 2003). On the other hand, many authors agree that the concept is very difficult for students to grasp and therefore discouraging (e.g. Schmidt and Jignéus, 2003). Therefore, to close the gap between what is and what could be, research results will have to be implemented into school practice, providing teachers with specific teaching materials and thus combining fundamental research with day-to-day practice.

Research findings about learning difficulties in stoichiometry and proposals for alternative concepts for teaching

Many studies on stoichiometry dealt with students' misconceptions (e.g. Mitchell and Gunstone, 1984; Schmidt, 1990; Huddle and Pillay, 1996; BouJaoude and Barakat, 2000). The main findings were that students

a. equate the mass ratio of atoms in a molecule with the ratio of the number of these atoms, and the mass ratio with the molar mass ratio (Schmidt, 1990),
b. calculate the molar mass of a given substance by summing up the atomic masses and then multiplying or dividing this sum by the coefficient of the substance in the chemical equation; others do not understand the significance of the coefficients in a chemical equation at all (BouJaoude and Barakat, 2000),
c. confuse the concepts of conservation of atoms and possible non-conservation of molecules or do not take into account the conservation of atoms or mass at all (Mitchell and Gunstone, 1984),
d. cannot determine the 'limiting reagent' in a given problem, when one substance is added in excess (Huddle and Pillay, 1996),
e. confuse or do not know the definitions of and relationships between stoichiometric entities in general (e.g. Furió, et al., 2002).

Other studies took a closer look on students' approaches to solving stoichiometric problems. In a large scale study in the 1990s Schmidt (1994) found out that German students (n = 4181, grade 11-13, age 16-19) mostly used three different strategies to solve stoichiometric questions that can be solved without arithmetical calculations and without a calculator:

a. a strategy using explicit calculation of the amounts of substance (‘mole method’),
b. a strategy avoiding explicit calculation of the amounts of substance and instead using the ratio of molar masses (‘proportional method‘) and
c. a strategy using mere logical reasoning (‘logical method’).

Interestingly, the large majority of the students used the ‘logical method’ (c) to get to the right solution rather than the algorithmic and more abstract strategies (a) and (b). Schmidt concluded that this is due to the fact that the given problems were easy to calculate. This was corroborated by a more recent interview study with a small sample of Swedish students (n = 4, grade 12, age 17-18) of Schmidt and Jignéus (2003). They found that for easy-to-calculate problems the participating students also used the ‘logical method’ but switched to a mathematical strategy e.g. (a) or (b), when confronted with a more complicated task. However, a study conducted in Hungary produced totally different results (Tóth and Kiss, 2005). The Hungarian secondary school students participating in this study (n = 750, grade 7-11, aged 13-17) almost never used the logical method but the mole method (most often), or the proportional method. According to the authors this might be due to the fact that the mole method is the one taught in Hungarian schools most prominently. On the other hand, the German students participating in Schmidt’s study had more chemistry lessons (three to five per week) than the Hungarian students (two per week) and were older in general. So they can be seen as relative experts compared to the Hungarian students and thus developed a logical method more easily.

In another study BouJaoude and Barakat (2003) investigated the relationships of students’ problem solving strategies in stoichiometry to their conceptual understanding and to their learning approaches (e.g. ‘deep approach’ vs. ‘relating ideas‘ vs. ‘intrinsic motivation’, etc., as defined by Entwistle and Ramsden, 1983). Based on results that indicated a connection between sound conceptual and procedural knowledge and successful problem solving, they administered a learning approach questionnaire (LAQ) and a stoichiometry test, partially followed by unstructured interviews, to forty Lebanese students (grade 11, age 16-20). Through the stoichiometry tests and the unstructured interviews they found many of the misconceptions described in earlier studies. They derived three main strategy types from the tests and the interviews.

a. Correct strategies, which were subdivided into ‘algorithmic’, ‘efficient’ and ‘messy’ strategies,
b. Incorrect strategies, subdivided into ‘incorrect strategies-incorrect answer’ and ‘incorrect strategies-correct answer’ and
c. ‘Incomplete’ strategies.

As the authors state, the majority of students participating in this study used algorithmic problem solving “*even when they did not have adequate understanding of the relevant concepts*” (pp. 24-25). In contrast to results in the literature, they did not find a correlation between the factors ‘learning approach’ and ‘conceptual understanding’. Furthermore, they did not find any patterns in the problem solving strategies used by students with different learning approaches.

In another study conducted by Frazer and Servant (1986, 1987) on titration calculations, the authors investigated which one of four possible expert methods was used by students solving two titration calculation problems. Three of the four methods were similar to those reported by Schmidt (1994) if one transfers the methods to this kind of problem:

1. A method deriving the reaction stoichiometry from the balanced chemical equation and using direct calculation of amounts of substance.

2. A method avoiding calculation of amounts of substance and instead using a proportion equation.
3. A method immediately converting the reaction stoichiometry into the quantities given in the text and continuing by using the 'unitary method' (see also Williams, 1980).
4. A method using the 'quantity calculus' and selecting and rearranging equations (see also Packer, 1980).

In the same study of a sample of 244 students only 79 written answers given to the two titration problems were correct. Most of the students used the method (1) to solve the problems, but less than a quarter of these responses were correct. Method (2) was the second most popular, but with poorest success. Method (3) was only used by a few students on the first problem. Method (4) was not used by any of the students. Although the results were poor in general, the authors came to the conclusion that using the second strategy is least recommendable since students only have to "*fill in the blanks*". In contrast, using method (1) may lead to an interlinked understanding of the chemical concepts.

The authors of all these studies give general advice on how to overcome the learning difficulties in the field of stoichiometry. Furthermore, some authors have developed alternative approaches on how to introduce subjects of stoichiometry in school. In Germany, Rossa (1998) for example, suggested visualization of the complex and the abstract entity 'mole'. Kaminski et al. (1994) developed a unit for introducing the chemical formula, setting aside the whole mole-concept and providing students with a table listing how many atoms one milligram of an element contains instead of giving them the molar masses. According to the authors, introduction of the mole-concept should thus be postponed. In other countries similar proposals were made, too. These can be classified into those which focus attention on conceptual prerequisites; those which use new analogies; and those which emphasize applications (for a review see Furió, et al., 2002).

Aims of our project: Combining investigation and development

The above mentioned studies on students' misconceptions in stoichiometry and students' problem solving strategies on stoichiometric problems give a detailed and thorough description of the status-quo. Additionally, alternative approaches show possible ways of coping with some of these challenges. However, as mentioned above, all these studies and developmental approaches were conducted separately. All these researchers give general advice on teaching, but specific materials based on empirical data are rarely provided. This is corroborated by a questionnaire-study conducted in Germany, in which teachers were asked which topics of chemistry were difficult to teach and why (Fiebig and Melle, 2001). The issue of 'basic chemical laws' (including stoichiometry) turned out to be 'difficult to teach', partly because of the lack of suitable teaching methods. This shows that the above mentioned combination of investigation and development should gain more attention in research studies, and that specific teaching and learning material should be developed on the basis of investigation results and should be thoroughly evaluated afterwards.

Furthermore, the proposed teaching material is mostly for introductory courses. Only little teaching material has been developed to help students while having to revise the topic of stoichiometry, dealing with the difficulties of partly understood concepts and partly consolidated knowledge. Thus the aims of our study were

1. to investigate the problem solving strategies German pupils (grade 9, having already been taught the issue of stoichiometry) use when solving stoichiometric problems and to determine the stages of this process;
2. to investigate the problems and misconceptions that occur in the solution process and to identify the relevant ones hindering this process;

3. to develop specific stepped supporting tools from the results in order to use on further problems of this type, especially for revision purposes.

Additionally, since in Germany the issue of stoichiometry is being introduced in grades 8 or 9 (depending on the federal state), one can expect students' problem solving strategies to be different from those reported by Schmidt (1994), because the students have less experience in problem solving in general than older students do, and they also know less about the underlying chemical concepts, such as the particle theory or the chemical equation (see above, and Tóth and Kiss, 2005).

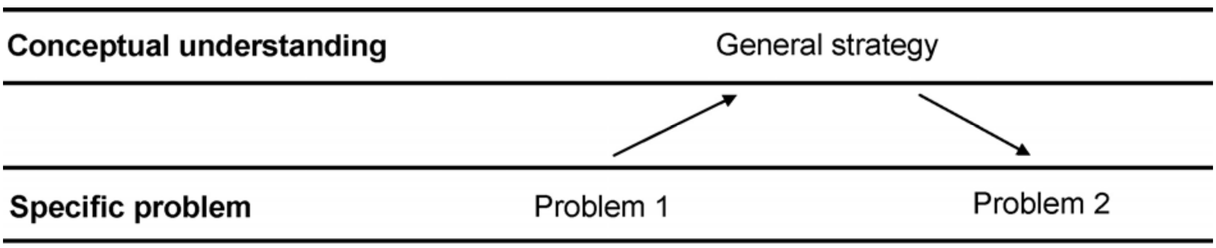
Method

Design of the interviews

One aim of our study is to take a close look at what students are thinking and how they are solving problems. To do this, interviews were conducted. Twenty students of five different classes of four secondary level schools (German Gymnasium) in Lower Saxony were interviewed. The issue of stoichiometry had been introduced in all five classes before. Four teachers participated in the study, one of them teaching two of the five classes. The students were chosen by their teachers. The teachers were told to choose two rather high-performing and two rather low-performing pupils, but since students had to volunteer to do the interviews, this was not always possible. The interviews were conducted by two of the authors (mostly T. d. B., partly M. F.) in rooms of the schools of the participating students and were audiotaped. Due to technical problems three audiotapes could not be used, so seventeen were eventually used for analysis (named student 1 to student 17 from hereon).

The interviews were planned according to the 'problem-centered interview' of Witzel (2000). According to this method, social data of the students was established with the help of a short questionnaire, which also included some general questions on chemistry in school that were referred to as the warming-up phase, and which prepared them for the main phase of the interview. These three parts are crucial to the 'problem-centered interview' method. In the main phase students were asked to solve two specific stoichiometric tasks, which can be classified as 'calculations based on reaction equations'. The two tasks were chosen as being typical for revision problems in the field of stoichiometry. Therefore, they are rather complex compared with the easy-to-solve problems Schmidt suggested for an introductory stoichiometry course. Furthermore, the students were to tell the interviewer their general strategy of tackling problems of this type in between the two solutions (cf. Figure 1). This setting was chosen to see whether the students were able to detach their process from that specific situation and whether the strategy is consistent with the one used for the second task.

Figure 1: Setting of the interview (modified after Parchmann, et al., 2006).



Another aspect of the setting deals with the phrasing of the tasks. As a consequence of the TIMS- and PISA-studies it is said that problems dealt with in German schools are phrased too often one-dimensionally and in a too formal and abstract way, since 'real-world problems' are usually more multi-dimensional and information has to be extracted from the text (cf. Ralle, 2001). In order to investigate whether a more realistic, therefore more complex phrasing of a problem has an impact on students' success of solving it, the first task was constructed in two different versions with the same chemical content, but with different texts: one was very formal (formal version), the other was put into a short context story (context version) (cf. Figure 2 and Figure 3).

Figure 2. The formal version of the first stoichiometric task (translation into English by the authors).

> Ammonia (NH_3) reacts with hydrogen chloride (HCl) to form ammonium chloride (NH_4Cl). Calculate what masses of ammonia and of hydrogen chloride are needed to produce 4 kg of ammonium chloride.

Figure 3. The context version of the first stoichiometric task (translation into English by the authors).

> "Kids and grown-ups love it so, the happy world of HARIBO!" Who does not like the dark brown liquorice and its lovely taste?! Tasty above all is the liquorice-plant. As another ingredient "ammonium chloratum" very often is used as an acidifier. This name is apothecary's jargon and the old chemical name of ammonium chloride (NH_4Cl).
> Ammonium chloride, also known as "salt of salmiak", is allowed up to 20 g/kg in liquorice by the nutrition laws.
> Ammonium chloride can be produced from ammonia (NH_3) and hydrogen chloride (HCl).
> You are a student trainee with HARIBO's. Suddenly the machine in which the ammonia and the hydrogen chloride are combined and added to the liquorice sounds the alarm, but your boss is in his office on an urgent telephone call and does not want to be interrupted. The valves controlling the doses of ammonia and hydrogen chloride have to be adjusted. You have to act quickly. It is very important not to overdose the ammonium chloride, because its amount in the liquorice is controlled regularly by an independent supervision agency.
> The machine produces ammonium chloride for a thousand bags of 200 g liquorice each.

Of the seventeen students, ten worked on the formal version and seven on the context version. The second task (cf. Figure 4), which was used to determine the stability of the strategy, was the same for all students.

Figure 4. The second stoichiometric task (translation into English by the authors).

> In industrialized states every tenth adult suffers daily, and every third occasionally, from heartburn. In Germany almost ten million people are affected by this disease. Helpful medicines against heartburn are the so-called 'antacids'.
> Antacids bound acids against an over-acidification of the stomach. The stomach acid contains hydrochloric acid (HCl, dissolved in water), which reacts with the antacid to form water, carbon dioxide and the corresponding salt. Generally, antacids are carbonates. Very common is 'Bullrichs salt', which uses sodium hydrogen carbonate as active ingredient. A single dose of an antacid is to be chosen in a way that it will react with two grams of hydrochloric acid. You are to formulate the instruction leaflet for a pharmaceutical company, which sells calcium carbonate ($CaCO_3$) as an antacid. The dosing instruction says that in case of heartburn, one tablet with sufficient water is to be ingested.
> But the specification, how many grams of calcium carbonate one tablet contains, is still missing…

While solving the two tasks students could rely on a preliminary set of SST, which were constructed on the basis of the procedure in chemistry textbooks. These tools mostly gave supporting information on stoichiometric entities and connections between them. In addition to the preliminary SST, the interviewer was allowed to ask questions regarding the solution, and thus was able to let the interviewee become aware of mistakes. All participants were provided with paper, pencil and a pocket calculator. The notes students took while solving the problems were collected for further analysis. The periodic table of elements (PSE) was handed out on demand, to see if students knew where the information for determining molar masses is given.

Students were asked to explain their process aloud while working on the solution ('think-aloud' technique). The explanations were audio taped, transcribed and analysed.

Development and selection of categories for analysis

The coding of the interviews was done in three steps. Firstly, the phases of the student's solution process were marked and the parts of the interview, in which students referred to their pre-knowledge, to the material given to them such as the task sheet, the PSE or the prepared preliminary SST, or to the interviewer's help or explanations and questions respectively, were coded. Maps were produced of these codes, showing the solution process and specifying the parts in which the interviewer had intervened (cf. Figures 5, 6 and 7). The maps were used to visualise the solution process and were used for interpretation alongside the coded transcripts. Secondly, the quality of the interviewees' knowledge was evaluated according to a coding scheme based on the facets of performance formulated by Duit et al. (2001, p. 172; cf. to the steps of 'scientific literacy', Bybee, 1997). In line with our research questions, we adopted the following five categories:

Recognition of facts and information in the material: Is the interviewee able to recognise necessary information given in the material or is he/she not?

Knowledge of facts, definitions, etc.: Which facts and definitions does the interviewee know?

Explanation of connections: Is the interviewee able to explain the connections between stoichiometric definitions and concepts or is he/she not?

Strategy: Does the interviewee know which steps to carry out to solve the task?

Process: Does he/she know how to do it; is he/she able to do it appropriately and by him-/herself?

In a third step, the students' problems and misconceptions were coded. The category 'problem' was used to indicate smaller problems in comprehension or with definitions. The category 'misconception' was used, when the interviewee showed severe misunderstanding of a concept even after the interviewer's inquiry.

After having extracted the strategies, we analysed these according to BouJaoude and Barakat (2003). The categories Frazer and Servant (1986) and Schmidt (1994) formulated were found to be only partly applicable, because due to the complexity-level of the two problems, none of the participants solved the two tasks by mere logical reasoning (cf. Tóth and Kiss, 2005). Therefore, these categories were used only on a side line (see *calculation strategy*). Furthermore, the problems and misconceptions were correlated with the problem-solving strategies to see at which step problems occurred and how they could be categorized.

The general strategy that the interviewees were asked to explain was coded according to its steps and eventually visualised in a map, too. His/her general (theoretical) strategy was compared firstly to his/her applied strategy, and secondly to the strategy of an expert. This was done for each student.

Results

Students' strategies

Within one map, the strategy, explanations of certain steps, gaps in the strategy with help activities and the problems and misconceptions of a student can be seen. These maps were first analysed independently, and afterwards compared to each other to see if general features can be seen. They have to be read in columns (cf. Figures 5 and 6). The middle column reflects the steps in the solution process used by the student. His/Her ability to explain the process or the strategy on his/her own account is marked by boxes placed on the left hand column. All interventions and help of the interviewer and the material are marked by boxes placed on the right hand column. Therefore, one can see at one glance, whether a solution strategy is made up by the student him-/herself or whether he/she needed help while solving the task. The strategy itself can also be seen in this representation of the interview data. The white boxes (middle column) show the solution strategy of each student applied to the problem and can easily be compared to the student's general strategy. Therefore, one can see whether the general strategy is different from the applied strategy in the two tasks. The yellow (correct) and green (incorrect) boxes mark the steps in the solution in which explanations are given by the student. The red boxes in the maps show those parts of the solution process in which the interviewer or the material helped the interviewee by showing him/her the mistakes and telling him/her how to continue. Additionally, the problems and misconceptions are linked to the solution process. These are shown by the blue boxes.

Figure 5. Solution process of student 1, task 1. Colour code: white boxes = strategy steps, yellow boxes = student is able to explain connections of chemical concepts, olive green boxes = student is able to explain the strategy, light blue boxes = problems with certain content.

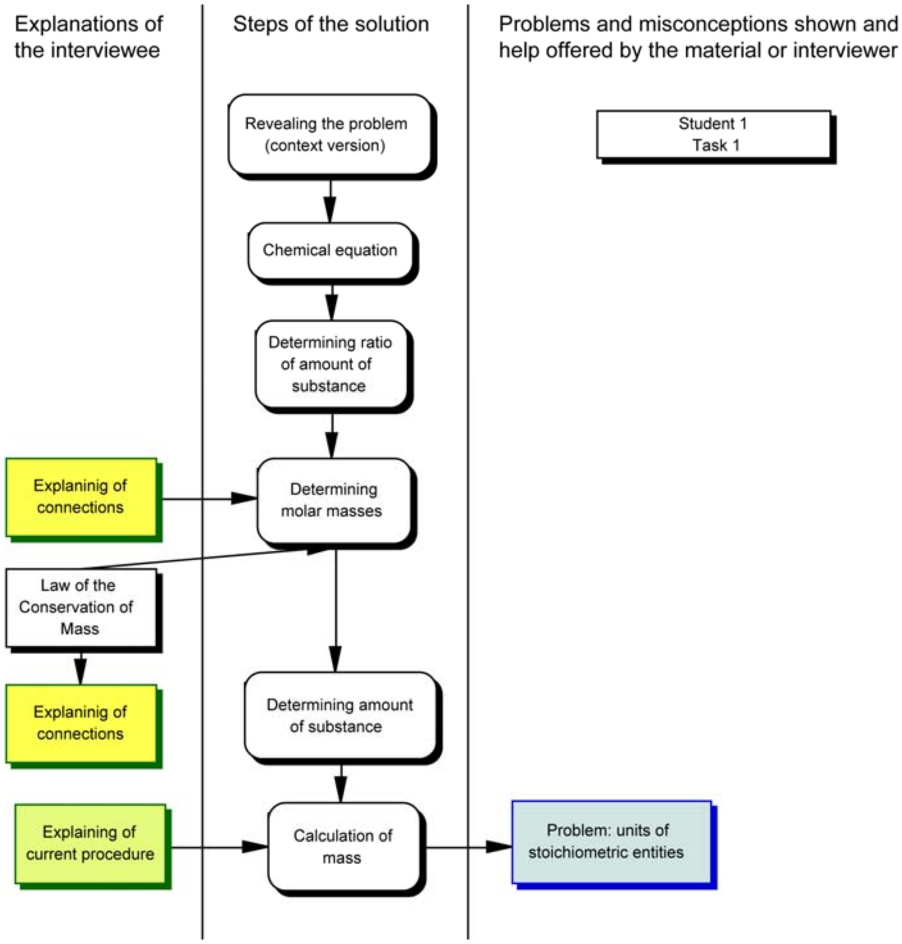
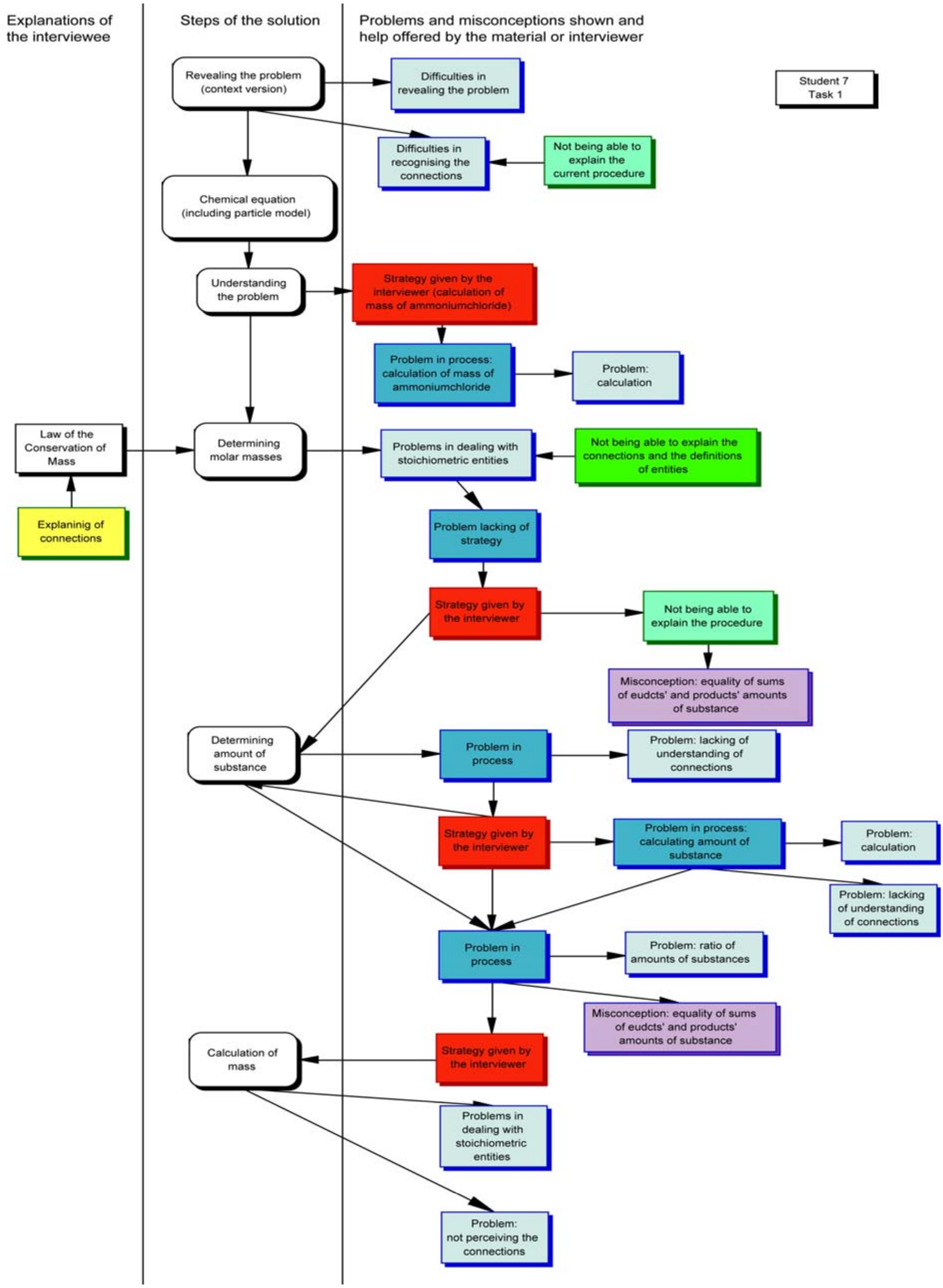


Figure 6. Solution process of student 7, task 1. Colour code: white boxes = strategy steps, yellow boxes = student is able to explain connections of chemical concepts, green boxes = student is not able to explain connections of chemical concepts, light blue boxes = problems with certain content, red boxes = strategy given by the interviewer, violet boxes = misconceptions, darker blue boxes = general problems in the solution process, turquoise green boxes = student is not able to explain the strategy.



The transcripts of the interviews and the maps show great individuality of the students' solution processes. At first sight, the map and thus the solution process seems to be unique for each student. All participants showed a variety of ideas and strategies, many of which led to correct answers. However, many misconceptions and problems reported in the literature were also found, which prevented some students from solving the tasks. In these cases the material and the interviewer showed the students the right way, since the goal of our study was to investigate which parts of the solution are most complicated and need special attention. Figure 5 and Figure 6 show the maps of two students for the first task, student 1 showing a self-contained and advanced strategy, whereas student 2 shows an unreflected, incomplete and chaotic strategy, which would not have succeeded without the help of the interviewer.

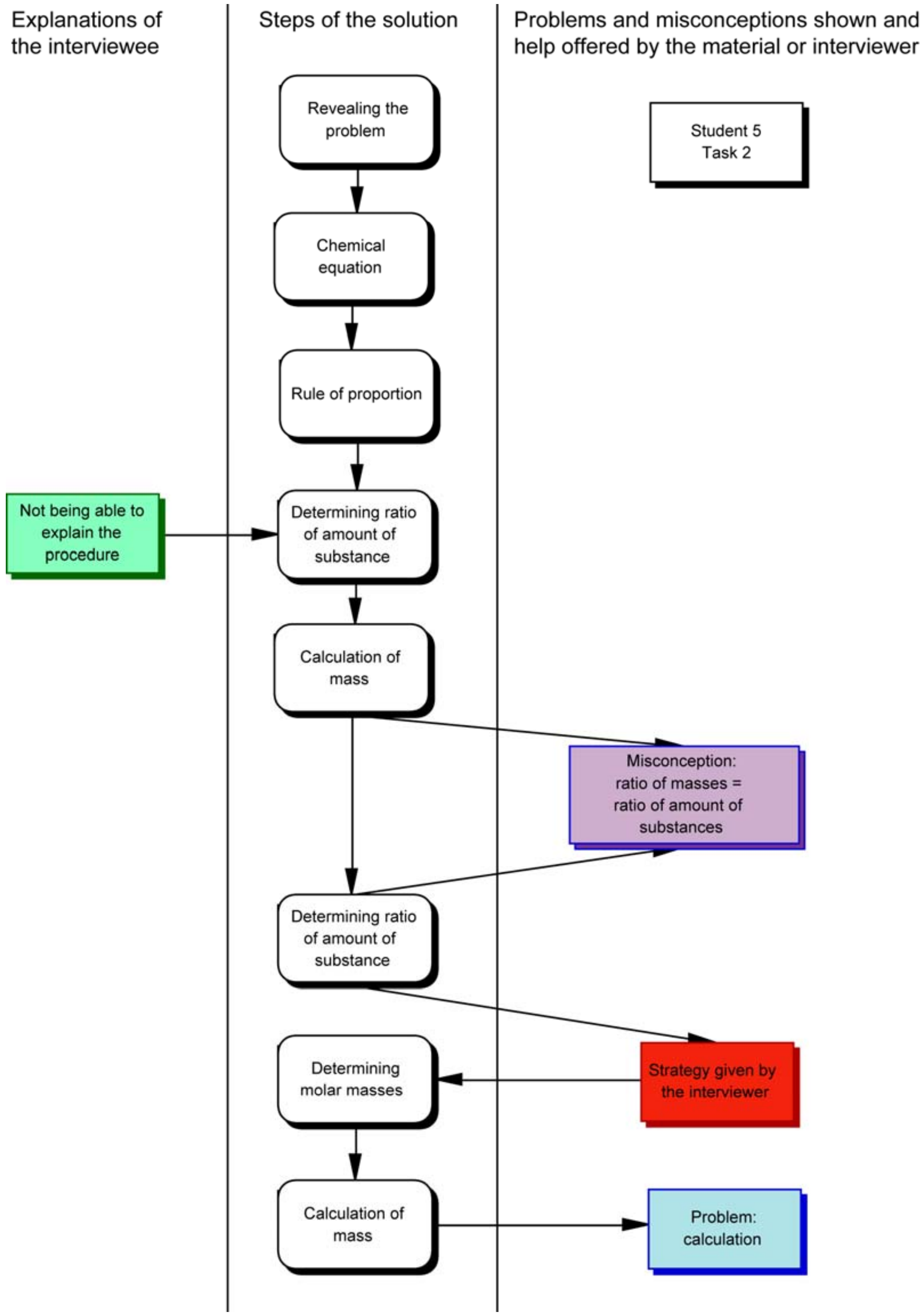
At second sight, one can see that all strategies contain up to six steps, which were sometimes combined with each other. These were:

- extracting the problem from the text given
- formulating the chemical equation
- calculating (the necessary) molar masses
- calculating the amount of substance
- considering the ratio of amount of substance
- calculating the mass.

Sometimes the step 'extracting the problem from the text given' was not explicitly mentioned by the students. One group of students combined the steps 'formulate the chemical equation', 'calculating molar masses', 'calculating the amount of substance' and 'considering the ratio of amount of substance' in a table which provided an overview of these entities. The order in which these steps were conducted sometimes varied between the interviewees. Since the step 'considering the ratio of amount of substance' did not need to be the last but one step, this was done right after formulating the chemical equation by some students. Another reason for varying the order of this scheme was that some steps were simply forgotten by the students, because they did not realise that all these steps are crucial when solving stoichiometric problems. Interestingly, students' not knowing *that* a certain step had to be done to solve the problem did not necessarily imply they did not know *how* to do this. Some students could perform steps correctly after having been told that this would lead to the correct solution by the interviewer or the preliminary SST. An example of a students' strategy showing this is given in Figure 7. The red box marks the step in which the interviewer said which step had to come next. The student, however, could then perform this step on his own.

From the maps it can be seen that it had no measurable impact on the solution process of the second task, whether the first task had been put in the formal version or the longer context-version. Generally, most students could cope better with the second task, but some still had severe problems. Only one of the students had more problems solving task two than she had had solving task one. Therefore, revision of stoichiometric terms and concepts seems to be an important factor when solving these problems repetitively.

Figure 7. Solution process of student 5, task 2. Colour code: white boxes = strategy steps, light blue boxes = problems with certain content, red boxes = strategy given by the interviewer, violet boxes = misconceptions, turquoise green boxes = student is not able to explain the strategy.



The nature of students' strategies

As mentioned above, the solution strategies were categorized according to BouJaoude and Barakat (2003). Since in our study students had the possibility to ask for help and thus mistakes were corrected during the interviews, which was both not the case in BouJaoude's and Barakat's study, the category 'incorrect answer' was not included. Rather, the nature of the help needed was categorized together with the solution strategy. Results are shown in Table 1.

Table 1. Categorization of students' problem solving strategies, based on BouJaoude and Barakat (2003).

Student	*Quality of the general strategy used by and quality of help needed by the student*
1	Algorithmic and reflective (efficient according to the stage of learning), needs little help on the second task.
2	Algorithmic, needs help during the solution of the first task.
3	Algorithmic, needs help during the solution of both tasks.
4	Algorithmic, needs help during the solution of both tasks.
5	Incomplete and messy, but on the way to an algorithmic strategy, needs help on both tasks.
6	Incomplete and chaotic, needs extensive help on both tasks.
7	Incomplete and chaotic, needs extensive help during the whole solution process.
8	Messy on first problem, needs extensive help, algorithmic on the second tasks.
9	Algorithmic, needs a key-word on the first task.
10	Algorithmic, needs a little help on the first task.
11	Algorithmic and reflective (efficient according to the stage of learning).
12	Incomplete, needs help on the first task, algorithmic on the second task.
13	Incomplete, mathematical-algorithmic, needs extensive help on both tasks.
14	Incomplete and chaotic, needs extensive help during the whole solution process.
15	Messy, but on the way to an algorithmic strategy, needs help on the first problem.
16	Algorithmic and reflective (efficient according to the stage of learning).
17	Algorithmic, needs help on the second task, difficulties with more complex tasks.

Table 1 shows that most students participating in our study either used an algorithmic and correct strategy, or an incomplete strategy in solving the problems, which meant that the latter students needed help while solving the tasks. Only three students showed a strategy which can be classified as 'reflective' or 'efficient to their state of learning'. For example, they calculated the mass of the second reagent in task 1 (cf. Figures 5 and 6) by using the law of conservation of masses and not by using the stoichiometric equations. However, while solving task 2 (cf. Figure 7), students only had to calculate the molar masses of hydrogen chloride and calcium carbonate to answer the question correctly, but every student started to calculate the molar masses of all three products, as well. Here they failed to apply an efficient strategy but used an algorithm ('calculate molar masses for all given substances') instead.

With most of the students, the general strategy and the applied strategies were almost the same, including the important steps and the order in which these were carried out. However, some of the students were only able to determine a strategy which reviewed the solution process of the first task, and thus was not independent from a specific given problem. Few others were unable to describe their general strategy after having solved the first task. These students were asked again to determine the strategy after they had solved the second task. If the general strategy obviously differed from the applied strategy on the first task, the interviewer asked further questions. In consequence, most students looked more carefully at their solution, identifying further steps. These were especially marked in the transcripts as being helped by the interviewer. The fact that some of the students were not able to describe a general strategy indicates that they are not able to abstract from a specific given task. This has to be discussed in the context of metacognition, but since it was only a subgoal of the study to investigate if the students' general and the applied strategies were the same, we shall not take it any further.

Calculation strategy – different kinds with different success

The strategies were then analysed further. The students were grouped according to their teachers, and the strategies of the students of one group were compared to each other both within groups and across groups. In this part of the analysis, we used the categories Frazer and Servant (1986) and Schmidt (1994) established. The maps show that the students used two different kinds of calculation strategies, some solving the tasks by using the stoichiometric equation

(1) $m = n \cdot M$,
(where m: mass, n: amount of substance, M: molar mass)

to calculate the amount of substance and then using the ratio of amount of substances for solving the two tasks. This is analogous to the 'mole method' as reported by Schmidt (1994). Others used the 'rule of proportion' or the 'rule of three' to calculate directly the required mass and thus avoiding the use of the concept 'amount of substance':

(2) $$\frac{M_1 \cdot n_1}{M_2 \cdot n_2} = \frac{m_1}{m_2}.$$

This is an analogous procedure to using the 'proportional method' as reported by e.g. Schmidt (1994). These students often multiplied the coefficients given in the chemical equation with the molar masses of the substances. Doing this on the one side leads to a correct answer, but on the other side shows an incorrect understanding of the concept of molar masses (cf. BouJaoude and Barakat, 2000; Frazer and Servant, 1986). Interestingly, the 'rule of proportion' method caused more trouble during the calculation, because students often mixed up numerators and denominators which led to false results. Table 2 shows the kind of calculation strategy used by the students and the problems that occurred.

Table 2. Students' strategies used for calculating the tasks and the nature of their difficulties.

Student	*Type of calculation strategy*
1	Equation, no problems during calculation.
2	Equation, problems with ratio of amount of substance during calculation.
3	Equation, problems with ratio of amount of substance during calculation.
4	Rule of proportion, problems with calculating masses and with amount of substance.
5	Rule of proportion, problems with calculating masses and with amount of substance.
6	Starting with rule of proportion, problems with calculating masses, after being helped switched to use the equation.
7	Mixture of rule of proportion and equation, massive problems with calculating.
8	Starting with rule of proportion, problems with calculating masses, after being helped switched to use the equation.
9	Rule of proportion, problems with calculating masses on the first task.
10	Rule of proportion, problems with calculating masses on the first task.
11	Equation, no problems during calculation.
12	Mentions the rule of proportion in the general strategy, but uses the equation in the applied strategies, problems with calculating masses and with ratio of amount of substances.
13	Rule of proportion, problems with entities and with ratio of amount of substances.
14	Starting with rule of proportion, problems with calculating masses, after being helped switched to use the equation.
15	Equation, problems with calculating masses and with amount of substance.
16	Equation, no problems during calculation.
17	Equation, problems with calculating masses and with ratio of amount of substances on the second task.

It can be seen that seven of the seventeen students used the equation to solve the tasks, while five used the rule of proportion. Often students of this latter group had problems when mixing up the given and wanted values, which may have been due to a simple mistake, but it could also have been due to a lack of understanding of stoichiometric entities like molar masses and amounts of substances. Another frequently observed problem concerned the ratio of amount of substance. Here both the students using the equation and the students using the rule of proportion had problems in applying the ratio correctly to their calculation. A third group, consisting of three students, started their calculations using the rule of proportion, but switched to using the equation after meeting problems doing the calculation, and being helped by the interviewer. The interviewer presented them the equation within one card of the preliminary SST. Interestingly, all these students coped better with the equation than with the rule of proportion. One said at the end of the interview that he will use the equation on all stoichiometric problems from now on instead of using the rule of proportion, "*because it all becomes easier*."[1] Of the remaining two students one mentioned the rule of proportion in his general strategy but actually used the equation while doing the calculation, another used a mixture of rule of proportion and equation. Both of them had the above mentioned problems in doing the calculations.

Influence of the teacher

An interesting observation can be made, when assigning the results of Table 2 to the groups formed by 'teacher-affiliation'. As mentioned above, the seventeen students were taught by four teachers. Students 1 and 2 were taught by teacher A, students 3-10 by teacher B, students 11-14 by teacher C and students 15-17 by teacher D. As can be seen in Table 2, the students of teachers A and D used the same mathematical strategy, that is, they used the equation to solve stoichiometric problems. In contrast, students of teacher B mostly used the rule of proportion, only one of them used the equation. Two of them switched to using the equation while doing the calculation. On these thirteen students it can be seen that they generally use a solution strategy, which was most likely the one taught by their teachers, and only occasionally applied a different strategy to these tasks. The four students of teacher C showed a somewhat different behaviour in carrying out quite diverse strategies, but this may be explained with the fact that their classes had been regrouped changing from grade 8 to grade 9, as one of those students said after the interview. Therefore, those students had probably been introduced to stoichiometry in different ways, because their previous teachers all showed them different methods of solving stoichiometric problems. This was confirmed by one student, saying that he was highly confused on how to best solve those problems, because the teacher in grade 8 had taught them differently from the teacher in grade 9. As expected, the way the teacher actually teaches stoichiometry seems to have a great impact on how young students solve stoichiometric problems and teaching should therefore be prepared with great care (cf. Tóth and Kiss, 2005).

Problems and misconceptions

Another aim of the study was to investigate which problems and misconceptions occurred within the solution process. Table 3 gives an overwiew of the problems and misconceptions found in the interviews.

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[1] All students' quotations were translated from German into English by the authors.

Table 3. Students' problems (p) and misconceptions (m) in the different steps of the solution process. The numbers say how many students had these problems and misconceptions

Part of solution process	*Problems (p) and misconceptions (m)*	*Number of students*
chemical equation	p: balancing chemical equation	4
	p: confusing 'atoms', 'molecules' and 'particles'	1
stoichiometric entities		
- non-specific	p: dealing with entities in general	9
	p: dealing with units	2
- molar mass	p: molar mass and coefficients/indices in chemical equation	8
	p: differentiating between independent entities (constants, e.g. molar mass) and dependent entities (e.g. mass)	5
	p: handling of PSE	7
- amount of substance	m: "*amount of substance cannot be less than one mole*"	3
ratio of amount of substance	p: realizing the ratio of amounts of substance needs to be taken into account	8
	m: "*sums of amounts of starting materials and products have to be the same*"	3
	m: "*ratio of masses = ratio of amounts of substance*"	4
mass	p: calculation	2
	p: two unknowns in one equation	3
	p: differentiating between independent entities (constants, e.g. molar mass) and dependent entities (e.g. mass)	3

As said above minor difficulties were classified as 'problems' and the category 'misconception' was only used when students showed severe misunderstandings of a concept. From Table 3 it can be seen that most problems occurred with regard to stoichiometric entities. Many students knew the definitions of these entities, but did not show a profound understanding, i.e. could not tell the connections between them. Some students mixed up stoichiometric concepts, revealing poor understanding, e.g.: "*The mole-number is, how many particles are contained in ... one u or in one atom ... something like that (student 17)*". These problems in understanding are described in previous studies, as well (cf. Furió, et al., 2002). Additionally, some problems occurred regarding the chemical equation. Most students knew that formulating the chemical equation is necessary for solving the task, but many did not know what information is provided in the equation, i.e. the ratio of amounts of substance. Therefore, they failed when the ratio had to be taken into account. One student put up the equation only with the names of the substances involved in the reaction and not with their chemical symbols. Being asked wherefrom he knew the ratio of the amounts of substances, he said: "*I don't know – gut feeling*" (student 3). Another great difficulty presented the 'ratio of amount of substance', which many students did not take into account or, as can be seen in the above quote, had no idea where to derive it from. Interestingly, only minor problems occurred doing the actual calculations.

Of the misconceptions described in the literature, many were found in our study as well. For example, four students equalled the ratio of masses with the ratio of amount of substance, as reported by Schmidt (1990). Another group of three students said that in a chemical equation the sums of the coefficients of starting materials and products and therefore their amounts of substance have to equal each other, as it is in a mathematical equation (cf. also

Figure 6, in which this misconception is shown). This indicates a misconception similar to the 'confusion of conservation of atoms and possible non-conservation of molecules', as reported by Mitchell and Gunstone (1984). One misconception that we found, however, has not been reported in literature, yet: "Amount of substance cannot be less than one mole". Thus,in task 2, the amount of substance of the hydrochloric acid is 2 g / 36.5 g/mol = 0.055 mol; three students stumbled over this; they wondered how an amount of substance could be less than one mole, as can be seen in the following two quotations (translation into English is by the authors).

S 6: 0.054794 ... uh, no, that's not possible...
I: Why not?
S 6: Because it's not even one mole. That's ... less than one mole.
I: And you're wondering about that?
S 6: Yes, I am.
[Pause for thinking – student 3 is thinking how to calculate the amount of substance of the hydrochloric acid]
S 3: OK, then I don't have a whole ... no, that isn't possible.
I: What do you want to calculate?
S 3: How many moles are in two grams ... of hydrochloric acid. But that has to be less than one mole.
I: Yes.
S 3: Is that correct?
I: If one mole is 36.5 g...
S 3: Yeah, but I mean is it correct that it's less than one mole?
I: Think about it for yourself. If one mole weighs 36.5 g ... and now you only have two grams...
S 3: I see that it's less than one mole. But I mean is it possible that it's like that?

A possible reason for the occurrence of this misconception is that in German chemistry lessons the mole is often introduced as a particle number rather than as an amount of substance. These students seem to believe that one mole *means the same as* one particle. Furthermore, the information that one mole is the amount of substance which represents the number of $6x10^{23}$ particles seemed to be meaningless for them, although they did know it. This is corroborated by other parts of the interviews in which the definition of one mole was repeated by all these three students. Nevertheless, they were not able to see that their calculation of the amount of substance of the hydrochloric acid was correct.

Discussion and implications – development of SST as teaching materials

If the students participating in this study solved stoichiometric problems correctly, they did it algorithmically. The fact that we chose contextualised problems with a rather complex setting did not show any effect on the strategy of solving the two tasks or the success in doing this. Solving stoichiometric tasks in this case included formulating the chemical equation, determining molar masses, calculating amount of substance, determining the ratio of amounts of substances and, finally, calculating the mass; therefore, these tasks can be classified as 'calculations based on the reaction equation'. The last three steps were either done in three separate steps by the students, using the stoichiometric equation, or combined in one step by calculating via the rule of proportion. The order in which the steps were carried out differed from student to student.

Nearly all students taught by the same teacher used a similar strategy, so the scheme the teachers used when introducing stoichiometry seems to have a great impact on students' solving strategies. This is in agreement with the results of Tóth and Kiss (2005), but in contrast to the results of Schmidt (1994). One possible reason for this is that the students participating in our study – like the Hungarian students participating in Tóth's and Kiss's study – were novices in the field of stoichiometry compared to the students participating in Schmidt's study. Beginners in solving these specific stoichiometric problems seem to tend to rely on a given structure, which may be due to the relative complexity of the solution of those problems, consisting of five single steps, rather than applying their own strategy which can be more efficient and thus save time. Therefore, an introductory stoichiometry course should provide students with a (self-developed?) scheme which includes all the necessary steps. From the fact that every student participating in our study used such a scheme, it may be concluded that this already happens in many classes and stoichiometry courses. With regard to the content of this scheme the data indicate that using equation (1) and thus explicitly using the term 'amount of substance' may be preferable to using the proportional equation (2) (see *calculation strategy*). This is corroborated by the results of Frazer and Servant (1986).

However, quite a lot of the students had only incomplete strategies for solving the tasks. If these students are to develop a viable strategy and thus are able to solve stoichiometric problems, they will have to be supported in their learning process, e.g. by SST. Three different kinds of incomplete strategies were found: To one group of students certain steps were unknown, and after being told they still did not know how to carry them out. A second group did know all the necessary steps but had problems in conducting single steps properly. Interestingly, a third group of students forgot that certain steps had to be carried out, but after being told, could do them correctly. In addition, some students had problems in working out the actual task from the given text, i.e. deciding which information is crucial for solving the tasks. Reviewing the calculation result for correctness was done only by very few students. From this, we derive four categories for SST. For this kind of stoichiometric problems given to a class for repetitive purpose, these SST may be:

1. A set of '(learning-) strategic SST'. These include general hints of how to work out the actual task from a longer text, and how to review the result and thus prove its correctness.
2. A set of 'content-strategic SST'. Here the steps of a possible solution are given, but only little information is provided on how these are carried out.
3. A set of 'content-related SST'. For every step of this solution, a detailed description is provided, which says how to do it.
4. A general glossary of important terms. Taking into account the difficulties many students had in explaining or defining stoichiometric entities correctly, an additional glossary of stoichiometric terms should be provided, giving background information and showing the connections between these entities.

The difficulties and misconceptions that were found in this study mostly occur with regard to the chemical content of the problems, i.e. the chemical equations and stoichiometric entities. Many difficulties and misconceptions described in the literature were found here too, but also an additional one that has not been described before. The actual calculation, i.e. doing the necessary mathematics, caused only minor problems.

Since quite a lot of new terms are being introduced within the topic of stoichiometry, which often sound similar to each other or include related concepts (e.g. the 'mole', 'molar mass', 'amount of substance', 'number of particles', etc.), beginners in stoichiometry should be given a chance to review these definitions while practising stoichiometric problems. This seems also appropriate because many misconceptions are likely to arise when definitions and connections of these terms and concepts are misunderstood.

The method used in this study works; however, it must also be seen critically. Since the interviewer was allowed to intervene in the solution process depending on the questions and problems of the interviewees, these interventions were highly individual and thus could not be planned a priori. The preliminary set of SST proved only to be partly applicable in most situations, but since it was the aim of the study to develop a sophisticated set of SST, this was assumed before starting the study. The interviewer has to act very carefully in the intervention phase so as not to push the students in a certain direction. Additionally, analysis has to be carried out thoroughly. Since the results of this study are corroborated by those of other studies, we think that the method is valid and can be transferred to other topics of science. For example, the first three sets of SST are likely to be appropriate for chemical problems in general. This is corroborated by the findings of studies on problem solving in chemistry (cf. Gabel and Bunce, 1994). A recent German study (ForschergruppeKassel, 2004) on physical and chemical problems on density, force and solubility found a combination of learning-strategic and content-related SST to be more helpful than either of them alone. For the more complex stoichiometric problems, the additional set of content-strategic SST should be added to help those students who have forgotten one of the several steps to be conducted.

The publication of the specific design of the SST is in preparation. Further evaluative research must show if this design is successful in helping students to solve stoichiometric problems, especially due to the fact that only seventeen students participated in this study. If it proves to be so, these categories for SST will be extended to other chemical topics. Thus, a catalogue of SST for chemical problems can be assembled and given to students to generally improve their achievement in chemistry.

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