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ABSTRACT

The purpose of this descriptive study was to create and test questions on stoichiometry with number ratios for quick mental calculations and to identify students' problem-solving strategies. The present study was a component of a more comprehensive investigation in which 7,441 German senior high school students were asked to work on 154 test items from 10 different topics. A random sample of 4,181 out of the 7,441 students completed the paper and pencil tests on stoichiometry. Additionally, discussions with students about how they solved the test items were videotaped. The study uncovered five strategies used by students to solve the test items on stoichiometry. With some test items the possibility that students came to the correct result though they had used incorrect solving strategies could not be excluded. However, it was possible to improve these test items. This indicates that students' successful solving strategies have to be known in order to decide whether a test item is valid or not. It was noted that most students successfully applied problem-solving strategies that were not presented in chemistry textbooks. The test items developed in the study and the problem solving strategies observed may be used to introduce students to stoichiometric calculations. (Author)

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Stoichiometric Problem Solving in High School Chemistry

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Abstract

The purpose of this descriptive study was to create and test questions on stoichiometry with number ratios for quick mental calculations and to identify students' problem-solving strategies. The present study was a component of a more comprehensive investigation in which 7,441 German senior high school students were asked to work on 154 test items from 10 different topics. A random sample of 4,181 out of the 7,441 students completed the paper and pencil tests on stochiometry. Additionally, discussions with students about how they solved the test items were videotaped.

The study uncovered five strategies used by students to solve the test items on stoichiometry. With some test items the possibility that students came to the correct result though they had used incorrect solving strategies could not be excluded. However, it was possible to improve these test items. This indicates that students' successful solving strategies have to be known in order to decide whether a test item is valid or not.

It was noted that most students successfully applied problem-solving strategies that were not presented in chemistry textbooks. The test items developed in the study and the problem solving strategies observed may be used to introduce students to stoichiometric calculations.

Introduction

Problems in chemistry can be solved correctly even if the examinees have not fully grasped the concepts involved. This is what **Yarroch** (1985) found in a study on high school students' difficulties in balancing chemical equations. **Gabel, Sherwood** and **Enochs** (1984) examined the problem solving behaviour of high school students working on stoichiometric problems. The majority of students solved the problems using only algorithmic methods, although they had been trained to use other methods requiring step-by-step reasoning. **Atwater** and **Alick** (1990) found that when solving items on stoichiometry college students were more successful if they applied algorithmic/reasoning strategies than they were using only algorithmic strategies. Investigating problem solving behaviours for chemical equilibrium problems **Camacho** and **Good** (1989) noticed that there was no clear dichotomy between problem solving behaviours of experts (doctoral students and faculty members) and novices (high school students, undergraduate majors and nonmajors). Particularly unsuccessful students, however, were looking for algorithms to find an immediate answer.

The present paper deals with the problem solving strategies which students apply to test items on stoichiometric calculations.

Background

The ratio of the amounts of substance of the elements of which a chemical compound consists can immediately be derived from the formula of the compound. As it is relatively easy to identify the masses by experiment, chemists are often interested in the relationship between amounts of substance and masses. This relationship is addressed in the test questions. Two possible types of test items deal with this problem. In type 1 the chemical formula of the compound is given and a statement of the masses of the elements involved is requested. In type 2 the masses of the elements are given and the chemical formula of the compound is to be deduced. This kind of test item can be solved using a basic equation that describes the relationship between the mass m, the amount of substance n and the molar mass M:

$$n = m/M \tag{1}$$

For binary compounds (compounds consisting of two elements) the basic equation has to be applied directly or indirectly to both elements.

If the formula is given and the mass ratio of the two elements $m_1:m_2$ is to be found, the correct answer is based on the following relationship:

$$m_1:m_2 = n_1 \cdot M_1 : n_2 \cdot M_2 \tag{2}$$

Here $n_1:n_2$ is the ratio of the amounts of substance of the elements involved, $M_1:M_2$ is the ratio of their molar masses.

Students are inclined to consider only two of the three variables m, n and M (Schmidt 1990). A frequent error is to equate the mass ratio with the amount of substance ratio:

$$m_1:m_2 = n_1:n_2 \tag{3}$$

This relationship is correct only if M_1 and M_2 are equal.

Another (less frequent) error is to equate the mass ratio with the ratio of the molar masses:

$$m_1:m_2 = M_1:M_2 \tag{4}$$

This relationship is valid only if n_1 and n_2 are equal, thus only if the calculations involve compounds with chemical formulae of the form AB.

- Relationship (2) can also be applied if the chemical formula is to be derived from the masses of the elements involved. If confronted with this problem students tend to deduce the ratio of the amounts of substance from the ratio of the masses. This means they apply equation (3).

Sometimes the ratio of the amounts of substance is derived from the ratio of the molar masses according to:

$$n_1:n_2 = M_1:M_2 \tag{5}$$

Relationship (5) is only valid if the calculations involve particular compounds. For example: for Cu_2S the ratios of $n_1:n_2$ and of $M_1:M_2$ are both 2:1.

In order to solve test items on stoichiometry one has to understand the relations described. Additionally, the calculations have to be performed correctly. If the calculations are too complex, students may disregard the chemical relations and fail. However, it is possible to design test items on stoichiometry that do not involve endless calculations.

Purpose of the study

In an earlier study (Schmidt 1990) it was noticed that a lot of students solving simple stoichiometric test items had developed their own problem solving strategies. The present study was aiming:

(1) to develop and test easy questions on stoichiometry,
(2) to identify the problem solving strategies that led examinees to correct results,
(3) to examine the relation between successful and unsuccessful strategies.

Method

Instruments

Two types of stoichiometric test items were designed according to a procedure that has recently been described (Schmidt and Beine, 1992). For items of the same type the formulation of the problem in the stem was basically the same, however, the individual test items contained different chemical formulae and figures.

In test items of type 1 the mass of an element was to be derived from the chemical formula and the mass of a compound. The calculations involved the formulae CuS_2, MgC_2, Cu_2Te, XO_2 and XY_2.

An example of this type is test item 1:

Test item1
The chemical formula of a copper sulphide is CuS_2. What mass of copper would be found in 6 g of copper sulphide? (The molar mass of copper Cu is 64 g/mol, the molar mass of sulphur S is 32 g/mol)

[A] 2 g, [B] 2.5 g, [C] 3 g, [D] 4 g

In test items of type 2 the masses of the elements were given and the chemical formula was to be derived. The calculations involved the formulae MgC_2, MoS_3, Cu_2Te, XO_2 and X_2Y. An example of this type is test item2:

Test item 2
6 g of an unknown element X contains 3 g X, the remainder being oxygen. Which formula fits this statement? (The molar mass of X is 32 g/mol, the molar mass of oxygen O is 16 g/mol)

[A] XO, [B] X_2O, [C] XO_2, [D] X_2O_3

The design of the test items allowed for a quick mental calculation of the answer which was achieved through the following characteristics:

- The chemical compounds chosen consisted of elements whose molar masses bear a simple ratio to one another. In test item 1 the ratio is $M(Cu) : M(S) = 64 : 32 = 2 : 1$.

-For the total mass of the compound a number was chosen that can easily be divided into two parts according to the ratio of the molar masses, the masses and the amounts of substance. In test item 1 the mass of 6 g CuS_2 can easily be divided into: $M(Cu) : M(S) = 2 : 1$, $m(Cu) : m(S) = 1 : 1$ and $n(Cu) : n(S) = 1 : 2$.

Design

The present investigation was part of a major project. The ten test items on stoichiometry were added to 144 test items dealing with nine other topics. Each student received a package of six items to be answered in one school period. The test items were randomly assigned to the students and to the position in the item packages. Each student could not get more than one test item on each topic. The random assignment was conducted in three steps. First the topics were randomly assigned to the 210 possible test packages (ten topics, six items per test package).

Next, the order of the topics in the test packages was varied. Finally, the items for each topic were randomly distributed into the test packages. The individual test papers were laser- printed.

The aforementioned random distribution of the test items was meant to rule out all possibility that the position of the test items in a test package could influence the result.

Data collection and sample

The data were collected during the school year 1989/90. A random sample of 4,181 out of 7,441 grade 11, 12 and 13 German high school students who had chosen an elementary course (three lessons of chemistry per week) or an advanced course (five lessons per week) participated in the stoichiometry test. Teachers were contacted and asked for their cooperation. A proportion of these teachers volunteered for the investigation. Therefore, the test population is not a completely random sample.

The test items were assigned to the students in a paper and pencil test. Students were not only asked to tick the answer they regarded as being correct, but also to give reasons for their choice. The number of options chosen was counted and students' comments on the options of the test items were gathered. Some of the test items were discussed in groups with students who were on a day visit to the University of Dortmund. The discussions were videotaped and later transcribed for analysis.

Findings

An analysis of students' answers to test item 1 provided the following data:

Table 1: Distribution of students' answers among the options for test item 1: 12th and 13th class, elementary course (e); 12th and 13th class, advanced course (a)

	option chosen in %					
course	A	B	C*	D	no answer	number of students
elementary	11	0	82	5	2	79
advanced	6	0	84	4	6	83

As was to be expected students gave relationship (3) as the reason for their choice of distractor A:

"CuS_2 contains one mol of copper and two moles of sulphur. Thus the ratio of Cu:S is 2:1."

Students who chose distractor D referred to relationship (4):
" Cu 64 g/mol, S 32 g/mol, 64:32 = 2:1 ... 6 g of copper sulphide contains 4 g of copper because the ratio is 2:1."

The students did not opt for the third distractor B of this item.

Three different strategies led the students to the correct result C.
Strategy 1 can be characterized by the following steps:
step 1: *to calculate the molar mass M of the compound*
$M(CuS_2) = 128\ g/mol$
step 2: *to calculate the amount of substance n of the compound*
$n\ (CuS_2) = 6\ g / 128\ g/mol$
step 3: *to calculate the amount of substance of the element whose mass is requested*
$n(CuS_2) = n(Cu) = (6/128)\ mol\ Cu$
step 4: *to calculate the mass m of the element*
$m(Cu) = n(Cu) \cdot M(Cu) = (6/128)\ mol \cdot 64\ g/mol = 3\ g\ Cu$

Typical of this strategy was that students calculated the amount of substance in step 2. It was applied by 2 % of the students who were successful in solving test item 1.

Strategy 2 begins in a way similar to strategy 1:
step 1: *to calculate the molar mass of the compound*
$M(CuS_2) = 128\ g/mol$
step 2: *to formulate a ratio:*
$M(CuS_2)/M(Cu) = m(CuS_2)/m(Cu)$
step 3: *to transform the ratio to*
$m(Cu) = \ldots$
step 4: *to calculate the mass requested*
$m(Cu) = 3\ g$

Typical of this strategy is the formulation of a ratio (step 2). 24% of the students who were successful in solving test item 1 used this strategy.

Strategy 3 differs from the two above:
step 1: *to formulate the ratio of the molar masses*
$M(Cu){:}M(S) = 64{:}32$
step 2: *to identify* $m(Cu){:}m(S)$ *by comparing* $M(Cu){:}M(S) = 2{:}1$
with $n(Cu){:}n(S) = 1{:}2$
step 3: *to split up the mass of the compound according to the ratio of masses 1:1*

$$6\,g\,CuS_2 = 3\,g\,Cu + 3\,g\,S$$

It is typical of this strategy that students use their own words, for example "twice as much", "same proportion", etc. to explain their strategy, avoiding mathematical expressions. 59 % of the students who were successful in solving test item 1 chose this strategy.
Here is an example of strategy 3. The response was divided into three steps according to the above pattern:

step1: "*The ratio of Cu to S in* CuS_2 *is 1:2. The ratio of the molar masses is ... 2:1 ...* "
step 2: " *Consequently, as far as the weight is concerned, one Cu is equivalent to two S.*"
step 3: " *Therefore one Cu has the same weight as two S. In this compound the Cu and the sulphur weigh 3 g.*"

Similar strategies occurred during group discussions with students. They were videotaped and transcribed later. 5 to 15% of the successful students used strategy 1, 15 to 20% of them strategy 2 and 50 to 60 % strategy 3 for solving the test items that were investigated.

An analysis of students' answers to test item 2 provided the following data:

Table 2: Distribution of students' answers among the options for test item 2, 12th and 13th class, elementary course (e); 12th and 13th class, advanced course (a)

	option chosen in %					
course	A	B	C*	D	no answer	number of students
elementary	6	10	79	1	5	150
advanced	5	7	85	0	3	158

As was to be expected students gave relationship (3) as the reason for their choice of distractor A:

" *3 g of O and 3 g of X, as there is one part O and one part X the formula is XO* "

Students who had chosen distractor B referred to relationship (5):
"*X_2O fits because oxygen weighs as much as X.*"

Two different strategies led the students to the correct result C.

Strategy 4 can be characterited by the following five steps:
step 1: *to write down the masses of the two elements*
$m(X), m(O)$
step 2: *to write down the amounts of substance of the elements involved*
$n(X) = m(X) / M(X); n(O) = m(O) / M(O)$
step 3: *to formulate the ratio of the amounts of the elements*
$n(X):n(O) = \dots$
step 4: *to calculate the least common multiple for the ratio of the amounts of substance*
$n(X):n(O) = 1:2$
step 5: *to deduce the formula XO_2*

Typical of this strategy is that the students wrote down the amounts of both chemical elements. 11 % of the students who were successful in solving test item 2 chose this strategy.

Strategy 5 differs from the aforementioned. It can be characterized by the following four steps:
step 1: *to write down the ratio of the masses*
$m(X):m(O) = \dots$
step 2: *to write down the ratio of the molar masses*
$M(X):M(O) = \dots$
step 3: *to deduce the ratio of the amounts of the elements by comparing*
$m(X):m(O)$ *with* $M(X):M(O)$
step 4: *to deduce the formula XO_2*

It is typical of this strategy that - like in strategy 3 - the examinees described the ratios between masses, molar masses and amounts of substance in their own words. 64 % of the students who were successful in solving test item 2 applied this strategy.

Here is an example of a student's response which is congruent with strategy 5. The response was divided into five steps according to the above pattern:

step1: " *Because the molar mass of the substance X is twice that of oxygen* "
step 2: " *and because each of the two substances comes to the half (3 g) of the total weight (6 g),*"
step 3: " *the number of the oxygen atoms in the compound has to be twice the number of atoms of the substance X,*"

step 4: " *which is expressed in the formula* XO_2."

All strategies described here were also communicated in the group discussions. 15 to 20 % of the successful students used strategy 4, 50 to 60 % of them used strategy 5 for solving the test items we investigated.

Discussion

The students were very successful in solving the stoichiometric test items, the success rate was approx. 80 %, both for elementary and advanced course students. This can be regarded as a good result if it is taken into consideration that the students did not revise for the tests.

Five strategies were used successfully to answer the test items on stoichiometry. Both strategies 2 and 3 are based on calculations of ratios of masses and molar masses, and both avoid direct calculation of amounts in moles, which is, however, necessary in the 'unpopular' strategy 1. This is also the pattern in the strategies identified in the case of item 2. In the 'popular' strategy 5, students start with ratios of masses and molar masses, and refrain from calculating numbers of moles, which is the first step in the less 'popular' strategy 4. It is open to discussion whether this happens because students encountered difficulties with the mole concept. Strategies 3 and 5 seem to be student variations of strategies 2 and 4. Some 20 teachers who were contacted said that they usually taught strategies 1, 2 and 4 in their lessons. In many German chemistry books students are advised to solve stoichiometric problems by using strategies 2 and 4. Strategies 3 and 5 occupy a special position because they are not mentioned in textbooks. It is typical of these strategies that students describe the relations in their own words. This indicates that the students did not adopt strategies they were trained to apply but created their own method instead. It cannot be ascertained to what extent students using strategies 1, 2 and 4 really understood the background of the procedure. However, as students created strategies 3 and 5, their appearance indicates that they used a reasoning strategy. In the present investigation high success coincides with a high proportion of reasoning. The problem-solving literature mentioned in the introduction shows that students tend to use algorithmic strategies. However, a reexamination of **Atwater**'s and **Alick**'s paper shows that the percentage of algorithmic/reasoning strategies increased with the success rate. For the group used in the study by **Gabel, Sherwood** and **Enochs** and by **Yarroch** the test items may have been too difficult. The students, therefore, may have fallen back on algorithmic strategies. **Camacho**'s and **Good**'s results equally show that the ability of a person to act as an expert applying reasonable problem solving strategies depends on the actual problem. The problem solving strategies of a person depend on the difficulty of the problem. If the problem is difficult, examinees tend to use algorithmic methods. If the problem is easy, they are inclined to applying reasoning strategies.

In order to be sucessful in solving the test items students have to consider the three variables m, n and M. If they apply strategy 2 in our example it is not certain that they also considered the third variable as they calculate according to the relationship

(6) $$n(CuS_2)/n(Cu)\cdot M(CuS_2)/M(Cu) = m(CuS_2)/m(Cu)$$

Here the quotient

(7) $$n(CuS_2)/n(Cu) = 1$$

does not influence the result. Thus items of the same type as test item 1 have to be improved by using calculations that involve formulae like AB_2 and with the mass of B being requested or by using calculations that involve formulae like A_2B and the calculation of the mass of A. If one formulates the improved items with different options of answers two distractors emerge from the incorrect relationships (3) and (4) and the third distractor emerges from

(8) $$M(A_2B)/M(A) = m(A_2B)/m(A)$$

The following test item would be an example:

Test item 3
The formula for copper telluride is Cu_2Te. What mass of copper would be found in 6 g of copper telluride? (The molar mass of copper Cu is 64 g/mol, the molar mass of tellurium Te 128 g/mol)

[A] 1.5 g, [B] 2 g, [C] 3 g, [D] 4 g

Students who apply strategies 3 and 5 compare $M_1:M_2$ with $n_1:n_2$ in order to get $m_1:m_2$. Or they compare $m_1:m_2$ with $M_1:M_2$ in order to get $n_1:n_2$. It is conceivable that the incorrect strategies (3), (4) and (5) are initial steps towards strategies 3 and 5. As some students have not taken the third variable into consideration they arrive at an incorrect result.

The teachers volunteered for the investigation and selected the classes on their own. However, the test items were randomly distributed to the 7,441 senior high school students. Each item was worked on by at least 100 elementary course and 100 advanced course students. The result is representative of all students who participated in the investigation. However, it is not known to what extent the results of our study can be generalized. The results can be validated by testing the questions with another population. The expenditure is small. If 20 students have worked on the test items the results can be analyzed and evaluated within half an hour.

Conclusions

The present study uncovered five strategies used by German senior high school students used to solve easy questions on stoichiometry. One group of items did not enable us to determine whether correct or incorrect considerations had led the students to the correct result. Therefore, the items had to be improved. This shows that students' strategies leading to the correct result have to be known in order to be able to decide whether or not a test item is valid.

It is characteristic of two of the five strategies that they are not mentioned in German textbooks and that students solved important steps by describing the relations in their own words instead of applying mathematical algorithms. It can be concluded that these students devised their own problem solving strategies.

The items can be solved correctly only if the three variables m, M and n are considered, but students' strategies led to incorrect results if they disregarded one of the variables.

It may be helpful to use students' strategies in schools in order to introduce stoichiometric calculations. These strategies, however, cannot be applied to problems containing unsuitable numbers. Therefore, they have to be developed into generally applicable strategies at a later stage using relationship (1).

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References

Atwater, M.M. & Alick, B. (1990). Cognitive development and problem-solving of afro-american students in chemistry. Journal of Research in Science Teaching, 27, 157-172.

Camacho, M. & Good, R. (1989). Problem solving and chemical equilibrium: successful and unsuccessful performance. Journal of Research in Science Teaching, 26, 251-272.

Gabel, D. L., Sherwood, R. D. & Enochs, L. (1984). Problem-solving skills of high school chemistry students. Journal of Research in Science Teaching, 21, 221-233.

Schmidt, H.-J. & Beine. M. (1992). Setting Multiple-choice Tests. Education in Chemistry, 28, 19-21.

Schmidt, H.-J. (1990). Secondary school students' strategies in stoichiometry. International Journal of Science Education, 12, 457-471.

Yarroch, W. L. (1985). Student understanding of chemical equation balancing. Journal of Research in Science Teaching, 22, 449-459.