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ABSTRACT

This study assumes that multiple choice test items generally provide the testee with several solutions, one of which is correct and the others of which are wrong. If pupils are unable to answer a question, one would expect that the wrong choices have equal chances of being selected. In many multiple choice items on stoichiometric calculation which have been studied over recent years, pupils were attracted to one or two wrong answers more than to the others. It is apparent that they have reached a wrong result by using a wrong answering strategy. The aim of this study was to develop new multiple choice test items involving stoichiometry in such a way that the correct and the two false answering strategies would lead to different results, to create items that include only number ratios which allow quick mental calculations and to determine whether on the new items pupils actually adopt false answering strategies. The strategy for developing questions and answer choices is discussed in detail. Instruments were administered to pupils in grades 11 and 12. This study concludes that when developing a test for classroom or research, items should include false and correct strategy application in the same proportion. (CW)

MIND THE RED HERRINGS - DELIBERATE DISTRACTION OF PUPILS' STRATEGIES SOLVING MULTIPLE CHOICE QUESTIONS IN CHEMISTRY

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Background

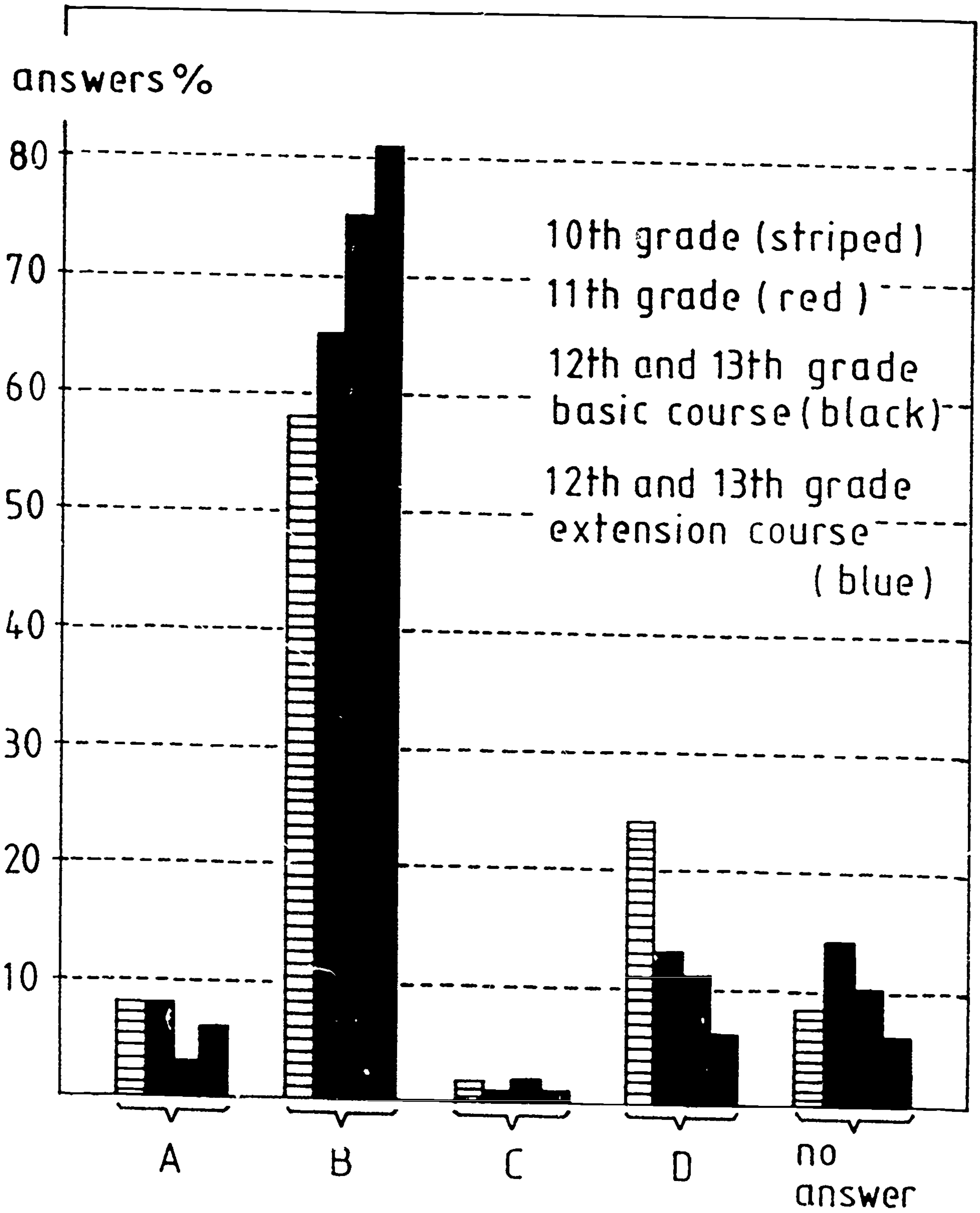
Multiple choice items provide the testee with several solutions among which he has to decide. As a rule there is only one correct answer and all the other answer options - the distractors - are wrong. If testees who are not able to answer the question were to decide on one of the answer options by chance, all of the distractors should be selected with the same frequency. In many of the multiple choice items on stoichiometric calculation which we have studied over recent years, however, testees are attracted to one or even to two distractors. From the explanations given by testees on multiple choice items for their answers in paper-and-pencil tests or in interviews, it is apparent that there is a system in the way they have reached the wrong result: they use their own answering strategies, which may well be quite cleverly thought out, but which do not quite correspond with the thinking of chemists. This matter can be clarified using an example.

> Test item 16,341
>
> The chemical formula of sulphur dioxide is SO_2. How many g of sulphur would be found in 6 g of sulphur dioxide?
>
> 4 g (A) / 3 g (B) / 2.5 g (C) / 2 g (D)

This item was given in the Federal Republic of Germany to a large number of grammar school pupils in the 10th to 13th grades. The correct answer is option B, many pupils however opted for distractors A and D (Fig. 1).

Fig. 1

Answer profile for question 16,341



From the pupils' comments it is possible to reconstruct the considerations which led them to these distractors. Many pupils who arrived at distractor D argue als follows:

"... O occurs in double the amount of S (because the formula is SO_2). If 2 g of S are present, twice as much O is present, i. e. 4 g."

These pupils procede from the the false asssumption that the amount ratio n(S) : n(O) can be equated with the mass ratio m(S) : m(O)

(1) $$n(S) : n(O) = m(S) : m(O)$$

Pupils arriving at distractor A argue along different lines:

"The atomic mass of oxygen is 16 u and of sulphur 32 u, that is twice as high as oxygen. They are therefore in a ratio of 2 : 1. Consequently 6 g of sulphur dioxide contain 4 g of sulphur."

These pupils equate the molar mass ratio M(S) : M(O) with the mass ratio m(S) : m(O):

(2) $$M(S) : M(O) = m(S) : m(O)$$

Similar pupil comments were obtained when pupils were handed only the item stem as an open-answer question.

It is interesting and important to note that the answer patterns for many items which have been used abroad can also be explained using the hypotheses expressed in equations (1) and (2). This justifies the assumption that the false strategies which have been outlined are also widely used abroad.

Problem

An obvious step is to take the false strategies used by pupils in dealing with items on stoichiometry as a basis for constructing new multiple choice items. The aim of this study was

/1/ to develop new items in such a way that the correct and the two false strategies would lead to different results (i. e. to different answer options),

/2/ that items include only numbers or number ratios which allow a quick mental calculation of the answer,

/3/ to determine whether on the new items pupils actually adopt the false strategies on which they are based.

Procedure

Instruments

If in solving multiple choice questions on stoichiometric calculation the correct and any false strategy are to lead to different answer options, it is necessary that the figures included in the item should be such that both elements of the binary compound differ from each other with regard to the amount ratio ($n_1 : n_2$), the molar mass ratio ($M_1 : M_2$) and the mass ratio ($m_1 : m_2$). The relationship existing between the amount, the molar mass and the mass is expressed in

(3) $$n_1 : n_2 = m_1/M_1 : m_2/M_2$$

One of the false assumptions described above involves pupils' failing to distinguish between the ratio of molar masses and of amount, or of molar masses and masses

(4) $$M_1 : M_2 = n_1 : n_2 \quad \text{or} \quad M_1 : M_2 = m_1 : m_2$$

In the other misconception which has been described they equate the mass ratio with that of amount of substance:

(5) $$m_1 : m_2 = n_1 : n_2$$

Let us now attempt to discover "by hand", so to speak, what compound and what further information are appropriate for a test on stoichiometry. For this purpose we will try out in turn various conditions.

For a compound of the type AB $n_1 = n_2$. Should the elements A and B of this compound in additon share the same molar mass, then also

$M_1 = M_2$. Under these boundary conditions the amount ratio, the molar mass ratio and the mass ratio are the same, i. e. although one or the other of our false strategies is used, the correct answer is still obtained.

It is not much better when an AB-type compound is selected where, however, the molar masses of elements A and B do differ. In this case the ratio of molar masses and the mass ratio coincide. Here too using a false strategy may still produce the correct result. This applies also in the situation where the molar masses of elements A and B are the same, but the formula of the compound does not reveal the simplest form AB. Under these boundary conditions the ratios of amount and mass are identical.

Let us now test whether a formula of the type AB_2 produces a better result. In this case $n_1 : n_2 = 1 : 2$. If in additon we make $M_1 : M_2 = 2 : 1$, it also follows that $m_1 : m_2 = 1 : 1$. We now look for concrete chemical elements for A and B whose molar masses are in a ratio of 2 : 1 and which combine as an AB_2-type compound. These should be compounds which do actually occur. We can consider here MgC_2, SO_2 and CuS_2. These formulae can be inserted into any number of item texts. Following the pattern of item 16,341, what is still missing is the value in the item stem with which the mass is to be calculated. This value can be set according to various principles. If one assumes that subjects calculate amounts by way of the quotient of mass and molar mass, it makes good sense to ensure that numerical values are used for this quotient which result in a whole number of a fraction. It is also conceivable that a correct answer could also be found by way of a ratio as is shown under (3). In this case an easily calculable figure can be obtained by taking as mass the "least common multiple" of $(n_1 + n_2)$ in equation (3), of $(M_1 + M_2)$ in equation (4) and of $(m_1 + m_2)$ in equation (5). In this case we obtain $(1 + 2) \times (1 + 1) = 6$. With that we have now rediscovered item 16,341 with option B as the key and A and D the two distractors. Distractor C is not associated with any misconception and is included simply as an intermediate value.

It is however also possible to incorporate one of the formulae developed and the mass value of 6 g into the text of an item in such a way that the masses of elements A and B are given and the required formula is asked for. The item would then have the form:

Test item 00.001

6 g of an oxide of sulphur contain 3 g of sulphur, the remainder being oxygen. Which formula fits this statement?

SO	$(m_1 : m_2 = n_1 : n_2)$	(A)
S_2O	$(M_1 : M_2 = n_1 : n_2)$	(B)
SO_2	$(m_1/M_1 : m_2/M_2 = n_1 : n_2)$	(C)

The brackets contain the steps of the calculation. They do not of course appear in the text of the item.

It is very unlikely that pupils will accept such improbable formulae as SO and S_2O as genuine alternatives to SO_2. If this type of item is to be retained, the element symbol S should be replaced by the symbol for the unknown element X with the molar mass of 32 g/mol.

The formula CuS_2, on the other hand, can be included in both question types:

Test item 00.002

The chemical formula of a copper sulphide is CuS_2. How many g of copper would be found in 6 g of copper sulphide?

2 g	$(n_1 : n_2 = m_1 : m_2)$	(A)
3 g	$(n_1 \times M_1 : n_2 \times M_2 = m_1 : m_2)$	(C)
4 g	$(M_1 : M_2 = m_1 : m_2)$	(D)

In this example a fourth answer option needs to be added, e. g. the intermediate value 2.5 g as distractor B. In the following item the formula is not given but asked for:

Test item 00,003

6 g of a sulphide of copper contain 3 g of copper, the remainder being sulphur. Which formula fits this statement?

CuS	$(m_1 : m_2 = n_1 : n_2)$	(A)
Cu_2S	$(M_1 : M_2 = n_1 : n_2)$	(B)
CuS_2	$(m_1/M_1 : m_2/M_2 = n_1 : n_2)$	(D)

Here also a fourth answer option, e. g. the formula Cu_2S_3 as distractor C, should be added. A very similar item has been received from an Examination Board in Great Britain and has been discussed in some of our publications. Consequently it has not been reused in the present study.

The previous discussion has been intended to clarify the principle on which we have constructed new multiple choice items on the basis of familiar answering strategies. It is obvious that a whole range of items can be obtained if for (5), (6) and (7) we insert simple number ratios like 1 : 2, 1 : 3, 2 : 3 etc. in various combinations. In order to "play through" systematically the different possibilities, a colleague of mine has designed a computer program. As I myself am not a mathematician I will not go any further into the computer calculations.

It is a matter of course that our insights into pupils' false answering strategies enable us as well to construct items in such a way that the pupils are meant not to adopt the above described wrong strategies. We have to decide between two possibilities:

/1/ If a chemical formula is given, it cannot be avoided that the calculation is made under the false assumption that the amount ratio $n_1 : n_2$ and the mass ratio $m_1 : m_2$ are identical. The only thing you can do is to find a particular compound with chemical elements of extremely different molar masses so that the molar mass quotient $M_1 : M_2$ results in a very high or low value and, moreover, appears as a so-called "dirty figure". The question is if this procedure actually keeps pupils from equating $M_1 : M_2$ with $m_1 : m_2$.

/2/ It is very much easier to construct test items with little possibilities for testees to use wrong strategies if a chemical formula is to be calculated. In this case the mass ratio $m_1 : m_2$ and the molar mass ratio $M_1 : M_2$ of the elements involved should also produce extreme values and dirty figures in order to confront the very pupil who calculates the amount ratio as a quotient of $m_1 : m_2$ or $M_1 : M_2$ with a completely unusual formula. A good example for such a formula is CBr_4 with $M_1 : M_2 = 12 : 80 = 3 : 20$ and $m_1 : m_2 = 12 : 320 = 3 : 80$. Hardly any pupil will accept a formula like $C_{12}Br_{80}$ and C_3Br_{80} or, rounded off, CBr_7 and CBr_{30}.

From the many items which we have developed and tested I would like to present to you just two as examples. This is the first one:

Test item 50,638

The chemical formula of a compound is XS_2. What mass of X combines with 16 grams of sulphur in this compound? The molar mass of X is 48 g/mol.

8 g	$(n_1 : n_2 = m_1 : m_2)$	(A)
12 g	$(n_1 \times M_1 : n_2 \times M_2 = m_1 : m_2)$	(B)
24 g	$(M_1 : M_2 = m_1 : m_2)$	(C)
32 g		(D)

As we know only two false strategies, so only two distractors can be calculated. Distractor D was added as an appropriate-looking complement.

This is the second test item:

Test item 50,644

40 g of a compound contain 16 g of sulphur, the remainder being molybdenum. Which formula fits this statement?

MoS_2	$(m_1/M_1 : m_2/M_2 = n_1 : n_2)$	(A)
Mo_3S_2	$(m_1 : m_2 = n_1 : n_2)$	(B)
Mo_2S		(C)
Mo_3S	$(M_1 : M_2 = n_1 \cdot n_2)$	(D)

Distractor C was added as an appropriate-looking complement.

Sample

At the beginning of the 1987/88 school year sets of test packages each for 30 pupils were sent to 21 grammar and vocational school teachers who had agreed to conduct the test. 17 teachers actually distributed the tests in classes. The returns from 353 pupils were useable for our evaluation. This figure is made up to 88 % of pupils in the senior level of grammar school, most of whom were in grade 11 or were taking part in Basic Courses in chemistry in grade 12. The remainder were attending vocational schools. 51 % of the subjects were male, 48 % were female. Neither the teachers nor the pupils were then chosen at random so that the sample cannot be regarded as representative in a statistical sense.

Data Processing

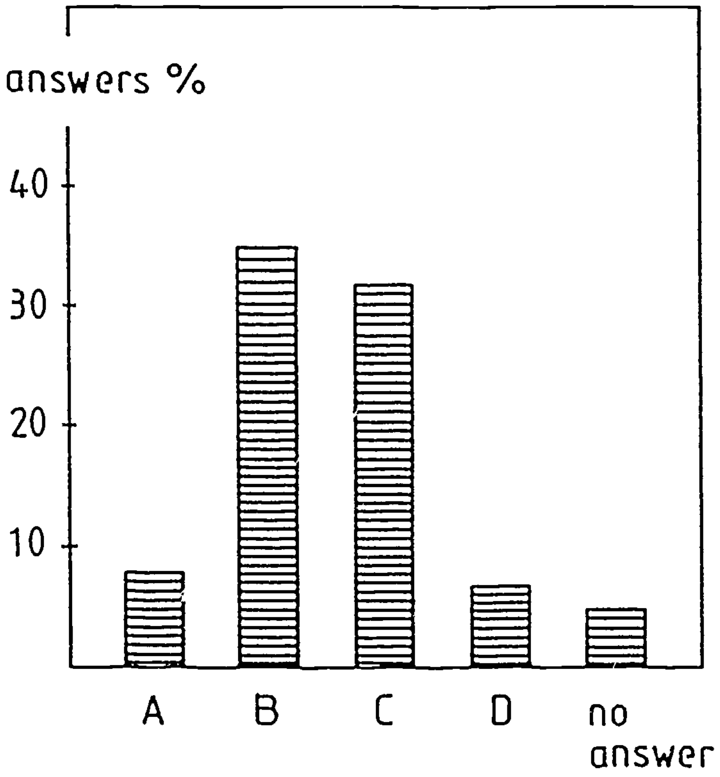
All the relevant information given by pupils on the personal questionnaires (age, school class, course etc.) and all the data which could be taken from the completed answer sheets (selected answer option, etc.) were coded and fed into a computer. Subsequently a frequency calculation was performed:

for each item the percentage of pupils selecting each answer option, or not answering, was calculated. From the explanations which accompanied the pupils' calculations it was attempted to reconstruct their answering strategies. Relevant sections of these explanations were put on file.

Results

Fig. 2 shows pupils' response rates for each of the answer options on item 50,638. This item was answered by [illegible]7 pupils. Distractor C is clearly the most attractive.

Fig. 2
Answer profile for question 50,638



Pupils' comments provide confirmation of the two false strategies on which the construction of the item is based actually being used. Here are two sample comments:

"As the compound has the formula XS_2 and consequently then there are twice as many parts S as parts X to be found, an amount of 8 g of X must be present since 8 g x 2 = 16 g."

This pupil draws on the strategy outlined under (5) and is led to distractor A. The next pupil uses the strategy described in equation (4). He writes:

"Molar mass of sulphur: 32 g/mol
Molar mass of X: 48 g/mol

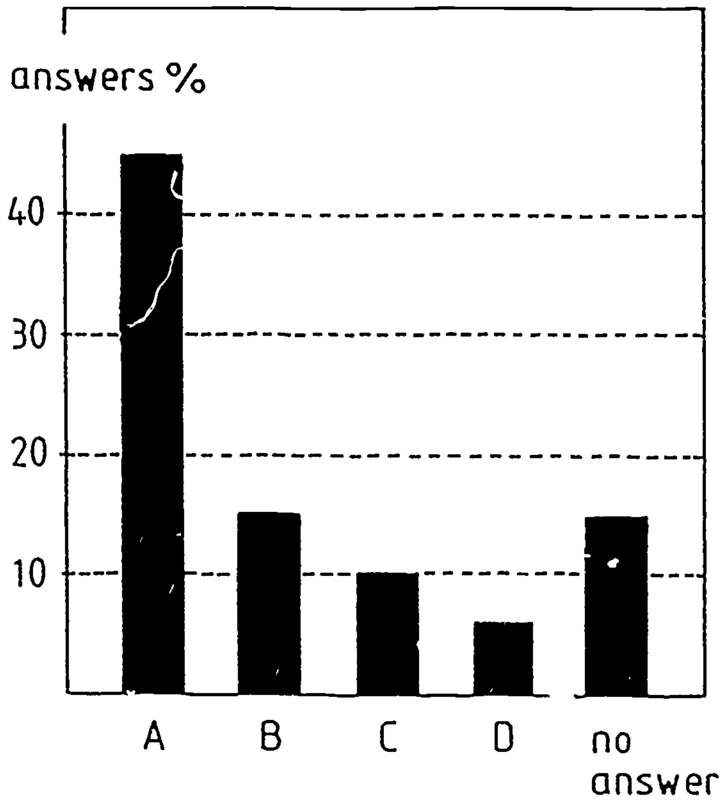
$$x = \frac{48\ g/mol \times 16\ g}{32\ g/mol} = 24\ g"$$

Following this path he arrives at distractor C.

In item 50,644 B is the most attractive distractor (fig. 3).

Fig. 3

Answer profile for question 50,644



This item was answered by 91 pupils. Here too the comments provide evidence that the main error was a matter of using two false strategies.

Here are two sample comments:

"40 g of the compound:

	molybdenum	*sulphur*	
	24 g	*16 g*	*/ : 16*
	1.5 g	*1 g*	

The ratio of sulphur to molybdenum is 2 : 3."

This pupil has drawn on equation (5) and selected distractor B. From the next comment it can be seen that the strategy expressed in equation (4) has been used. This has led to distractor D.

"Relative atomic mass of molybdenum: 96 g/mol
Relative atomic mass of sulphur: 32 g/mol

$$\text{Ratio} \quad \frac{\text{molybdenum}}{\text{sulphur}} = \frac{96\ g/mol}{32\ g/mol} = 1/3\ mol"$$

Trial has therefore led to the expected result. It has however also produced one surprise. Let us look again at the answer profile for item 16,341 (fig. 1). For all the items we have ourselves tested, the distractor which has been most attractive has previously always been that based on strategy (5), the failure to distinguish between the ratios of mass and amount. This applies, for example, also to item 50,644 (fig. 3). With item 50,638 an item has however now been added for which the most attractive distractor is clearly the one based on strategy (4), the failure to distinguish between the ratios of molar mass and mass (fig. 2). Similarly in the items from Great Britain, for which the answer profile is known to us, it was always the distractor associated with strategy (4) which proved most attractive. Whenever we have distributed tests on stoichiometry, the set of items has always had appended to it as the final sheet a list of the molar masses of familiar elements. In the tests from Great Britain the molar masses were included in the very text of the item. Our hypothesis: the majority of pupils try to make do with those numbers which appear in the stem of the item. However, they also try to make do with as few numbers as possible.

Perhaps what happens when pupils attempt an item on stoichiometry is that they allow themselves to be led by the number ratios and only later attribute to them any chemical significance. If this is the case, pupils would be acting like good scientists. When Avogadro developed the law which bears his name he was at first impressed by the simple proportions which had been found in gas reactions. As he attempted to bestow an interpretation on these simple proportions his law was formed. The periodic system of elements was developed in a similar way.

The explanation which has been given for the different answer profiles strikes us as extremely plausible, but it has at present only the status of a provisional hypothesis as the empirical basis for its support is still too small.

Conclusion

Items on stoichiometric calculations can be developed in different ways:

/1/ If a chemical formula is to be developed, the test can be constructed in such a way that pupils can actually make the errors they are keen on making. But it is also possible to keep them from error-making.

/2/ If, however, a chemical formula is given and masses are to be calculated, pupils can always draw on the false strategy $n_1 : n_2 = m_1 : m_2$. Perhaps the answering strategy $M_1 : M_2 = m_1 : m_2$ can be made less attractive.

In chemistry lessons the different tests described above may be used for individual purposes. It is very important that in chemistry lessons pupils think about the errors they are so keen on making. In order to maintain awareness of the cause of the error, problem areas must be reviewed during lessons on a regular basis and in various guises.

When adopting norm-referenced tests for assessment or analyzing treatment effects in empirical research, the individual items should allow fair comparison on equal level. In classroom tests for example pupils should be given the two different types of items - false strategy applicable/not applicable - in the same proportion.

Consequently, a great variety of tests is required. In this study it has been revealed that it is very easy to develop items on stoichiometric calculation.