International Journal of Science Education

ISSN: 0950-0693 (Print) 1464-5289 (Online) Journal homepage: http://www.tandfonline.com/loi/tsed20

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To cite this article: Jack A. Rowell , Chris J. Dawson & Harry Lyndon (1990) Changing misconceptions: a challenge to science educators, International Journal of Science Education, 12:2, 167-175

To link to this article: https://doi.org/10.1080/0950069900120205

Published online: 09 Jul 2006.

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INT. J. SCI. EDUC., 1990, VOL. 12, NO. 2, 167–175

Changing misconceptions: a challenge to science educators

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In this paper we examine misconceptions as personal explanatory knowledge judged by experts in the field to be in error. To those who have constructed them, misconceptions are not recognizable as different from any other explanatory knowledge: they are formed by the same process, take part in the generation of new knowledge and consequently are difficult to replace. As with construction, replacement involves the processes of equilibration. To date, educational strategies promoting equilibration in the classroom have attempted this through co-operative debate, using the teacher as chairman and *agent provocateur*. Here, we briefly discuss the epistemological status of an alternative to co-operative debate that is more teacher centred, and report on a comparative empirical test of the educational potential of the two strategies.

Introduction

While there has been a wealth of published research identifying misconceptions in the understanding of scientific concepts by students, relatively little has appeared detailing how misconceptions might best be changed, and why any proposed strategy might be expected to work. Good reasons can be advanced for this ordering of events. For example, researchers needed to know the pervasiveness of the problem faced, and, even more to the point, they needed to know that misconceptions could be recalcitrant in the extreme. These facts are now clear, however. What is needed is a coherent explanation of their occurrence, their resistance to change, and teaching strategies that could help to overcome this resistance. Piaget's theory of knowledge provides that explanation.

In a recent paper concerned with Piagetian epistemology and the teaching of science (Rowell 1989), it was argued that Piaget's theory is distinctive in that its core consideration is the dynamics of knowledge growth. Within the theory, knowledge growth at all levels, individual, social, and historical, receives a coherent explanation in the principle of equilibration. In this paper, however, we shall restrict our concern to the individual level. We shall report some preliminary work comparing equilibration-based classroom strategies for overcoming misconceptions and promoting knowledge growth in individuals, and will offer explanations for their differential efficacy.

Let us start with a brief comment on our use of the term misconceptions, which, following the Piagetian distinction between inductive and constructive generalizations, we shall reserve for 'errors' of some kind in the latter. By misconceptions, then, we shall mean both explanatory (i.e., theoretical) knowledge judged by experts in the field to be limited, but on the right track, and that judged to be wrong. Such misconceptions are reliable aspects of an individual's theoretical knowledge. They

0950–0693/90 $3·00 © 1990 Taylor & Francis Ltd.

are made evident by the consistent use of a false explanation, or the over-generalization of a limited one, given in answer to particular problem or problem kind.

From the Piagetian viewpoint, misconceptions are constructions and the processes of their construction are those of equilibration. Thus, like all explanatory knowledge, the construction of misconceptions starts with the recognition of a knowledge 'gap' of some kind. Dependent on what is already known, and on the range and sequence of experiences faced, including those contrived by teachers, construction continues with the creation of potentially gap-filling possibilities from which a selection is made, and often subsequently modified. The resulting knowledge, the misconception, is the 'best' the individual has managed to produce to that point in time, and is the starting point for any further progress irrespective of whether it is limited or wrong. Almost undoubtedly that knowledge has been successful in some situations. However, when judged by someone with a better theory* it is successful only 'up to a point'.

For us, then, the important features of misconceptions are, first, that for individuals misconceptions are knowledge and that, for them, this knowledge is no different from any other knowledge that they have constructed. In consequence, misconceptions are potentially progressive aspects of the thinking process, as Karmiloff-Smith and Inhelder (1975, p. 209) maintain. Second, misconceptions are successful in that they make sense of an aspect of the individual's environment, albeit only 'up to a point'. What this latter qualification means, simply, is that what a person operating a misconception interprets as an anomaly, and possibly in need of a different explanation, a second person operating a better theory sees as a counter-example refuting the incorrect, or limited knowledge of the first.

What will convince the first individual to change, or even acknowledge that change is needed? These matters have been argued elsewhere (Rowell 1983, 1989, Rowell and Dawson 1983, 1985), and for brevity we shall only state the conclusion, which is examined further in the research to be reported here. Our conclusion is that for optimal rate of progress in overcoming a misconception that is false, and possibly even one that is limited, students should first construct another potentially relevant, potentially contradictory, better explanation. This explanation should be firmly based on aspects of their knowledge structure which, although not spontaneously used, are familiar to them. The point of this exercise is that, as in the growth of science itself where a new and better theory usually must emerge before the old one is discarded (see, for example, Lakatos 1974, p. 119), if an individual has successfully constructed a new and intrinsically better theory, that person is in a position to rationally argue, with her/himself and with others‡, the pros and cons of which theory to retain.

For instruction, one possible stumbling block is the 'if' qualifying successful construction of the better theory. To be an effective competitor the new theory must be on an 'equal' mental footing with its rival, it has to be understood and it has to be believable (Rowell and Dawson 1988). There are other stumbling blocks, however. For co-operative debate to be possible, at the social or intra-individual level, *both*

* For Piaget, 'better' is a result of improving equilibration, such that more possibilities are available for interacting with a wider environment (see Vuyk 1981, p. 156).

‡ Through participation in social co-operation individuals become capable of criticizing and evaluating ideas by taking different viewpoints, even in the absence of others (see Kitchener 1981, p. 265).

theories and their respective expectations must be unambiguously identifiable and discriminable by individuals, because the essence of debate is the juxtaposition of arguments, followed by rational conviction and elimination, or restriction, of the defeated idea. In equilibratory terms, it is a matter of generating possibilities and selecting from them on the basis of both exogenous and endogenous criteria. Does the expectation fit the facts? What is its relation to what is already known and organized? Does it take account of previously effective procedures? (See Piaget and Voyat 1979).

A potential problem, then, is the necessary confrontation of ideas. Without it, students may publicly accept a better theory only because they can mount no argument against it. They may even be able to operate the better idea successfully under some circumstances. However, this is not the same as rejecting their established ideas, which, theoretically, will not occur if they personally have not produced and resolved the conflict, irrespective of whether they are capable of doing so. Clearly, in co-operative debates involving whole classes of students, it is very difficult for a teacher to know if equilibration has occurred for individuals. Suffice it to say that our previous attempts to use the methodology of teaching a better theory first, followed by co-operative debate (Rowell and Dawson 1985), have proved successful only for some students. Can this state of affairs be changed?

A possible instructional alternative to co-operative debate

It is stating the obvious to say that the initial teaching of a better theory should be as effective as possible, but is there an alternative to co-operative debate that could be a more effective *instructional* tool for ensuring equilibration by a greater number of individuals?

Over the course of the last decade one of us (HL) has been concerned, in his profession as a school psychologist, with the remediation of a range of difficulties apparent in primary school children: problems with spelling, problems with writing legibly, even with toe walking. His technique for doing this (Lyndon 1989), which has achieved considerable success in these areas, has some provocative features from a Piagetian viewpoint, especially for someone who advocates the teaching of a new theory as a first step in overcoming misconceptions.

Briefly, let us consider the technique as it is used for the correction of spelling errors. Suppose the child spells friend as 'frend'. The teacher asks the child if s/he may call 'frend' the 'old way' of spelling, thereby labelling it for the child. The teacher next asks if she may show a 'new way' of spelling the same word, writes 'friend', and points out both the differences and similarities of the two spellings. The child is now asked to produce his/her 'old way', then the 'new way', and to say how they differ. This is repeated five times. The child is next asked to use only the new way of spelling 'friend' in the context of six sentences [the five and six, respectively, are numbers of repetitions established empirically as necessary and sufficient]. This sequence is referred to as a 'trial', and it has been found necessary to use four or five trials spaced at around two-week intervals to ensure spontaneous, appropriate use of the 'new way'. The essence of HL's procedure is, first, that the reactivation of 'errors' [old ways] is necessary for their elimination; second, that the labelling of competing knowledge, its systematic discrimination, and the generalization of the 'new' [its use in a variety of appropriate contexts] are all needed for 'error' replacement. For ease of reference, we shall refer to the technique as OW/NW.

HL's work with OW/NW has been with the remediation of knowledge at the rote end of the scale of meaning. For example, there is little meaning available to the young child in a spelling change from 'frend' to 'friend'. However, could the technique, indeed should the technique work for changing misconceptions, i.e., 'errors' in explanatory, meaningful knowledge? 'Could it work?' invites an empirical response of 'let's try, and see what happens'. 'Should it work?' calls for a theoretical analysis. As we shall argue, when considered from the Piagetian viewpoint, we think it should work. Our exploratory classroom study, to be reported later, supports this position, showing that it can.

Why should OW/NW work? Briefly, because it is an instructional analogue of the steps of the equilibration model, *provided that* teaching of the better theory [the new way] has resulted in its construction, hence understanding by the individuals concerned, and is, therefore, a source of possibilities for problem solution. Piaget (1979) found that teaching that stimulates the child to construct new, compelling possibilities, by building on ideas available but not spontaneously used, can be a powerful agent for precocious equilibratory change, even of such basic structures/ processes as are involved in conservation. Equilibration is concerned with the resolution of 'what is' and 'what is not, but might have been'; it is concerned with the creation, selection, and modification of possibilities. As outlined, the OW/NW sequence directs attention to the competing possibilities, helping, even in a whole class situation, to ensure that *both* they, and their derivative empirically observable expectations, are juxtaposed and clearly discriminated by individuals for comparative assessment with each other and with reality. OW/NW, in other words, provides greater instructional control than co-operative debate over those features of a situation to which both apply, and which are vital to the operation of equilibration. OW/NW does not restrict debate, but does direct it. Any student can raise any problem deemed appropriate to the explanatory ideas under examination. However, when they do, the problem is examined in terms of a framework of 'old' and 'new' possibilities.

Empirical epistemology: a comparison of alternative procedures for changing misconceptions

Does OW/NW work? More to the point, does it work any better than co-operative debate? To make a start on answering this question we chose as our topic the explanation of displacement volume, and obtained the assistance of a local primary school with three, non-streamed classes of year 7 students. On the basis of knowledge gained from previous work with volume (for example, Rowell and Dawson 1983), we predicted that many students at this year level would have misconceptions concerning the explanation of displacement volume. We were not disappointed.

Assessing misconceptions

The test of conservation* devised by Rowell and Renner (1976) was used to assess the number and kind of misconceptions about volume held by our sample of year 7

* The test differs from others in providing an assessment of whether apparent non-conservation of volume is based on a logical argument that plasticine may be compressed when rolled, or squeezed into another shape. We found no evidence of this in our students.

students. The foci of our attention were students' predictions and explanations of displacement volume. Students were shown two identical beakers part-filled with water and were asked to predict the water level rise in each if a ball of plasticine was immersed on one [X], and a sausage produced from another ball of equal weight was immersed in the second [Y]. Specifically, the question asked was, will the water level rise by the same amount in both, or be greater in X, or greater in Y? Students were then asked to explain their answer.

We found that 19 of 22 children in one class [for ease of reference we shall call this class A], 16 of 18 in another [B], and 15 of 20 in a third [C] [these are numbers of children for whom we have full information], had misconceptions concerning volume; this was in spite of the fact that all had recently completed a sequence of units in arithmetic devoted to the concept.

Not all misconceptions were the same, of course; they differed in kind, being either limited or false, and when limited, they differed in the nature of their limitation. Thus, ten children in class A, five in B, and six in C, explained displacement volume in terms of object weight; a false theory. For these students heavier objects displace a greater volume of water, but because they conserve weight these individuals also conserve displacement volume across shape change of the object. Of the remaining nine children with misconceptions in A, four predicted that displacement volume would change if the shape of the object were changed, one was unable to make a prediction, and four used the potentially ambiguous term 'amount' rather than volume. In B, eight used shape as the basis of their explanation, two used amount, and one used what he named 'size', but distinguished from volume. In C, three used shape, one used mass, one used surface area, one could offer no prediction, and three used amount.

Equilibration-based strategies for changing misconceptions

To test the efficacy of OW/NW in comparison with co-operative debate, three teaching strategies were devised and randomly paired with classes. Class A was taught the better theory, that object volume explains displacement volume, and followed this with co-operative debate of selected questions. Class C was taught the better theory, and followed this with the OW/NW strategy. Class B was given the OW/NW strategy only.

For reasons of space, we shall describe the essence of each strategy as briefly as possible, starting with teaching the better theory. For the latter, lesson length was approximately 30 minutes. Both A and C were taught by the same teacher [CJD].

Teaching the better theory

For object volume to provide a better explanation of displacement volume than weight children must appreciate that 'volume' is a word used to refer to a measure of space occupied, which is conserved across shape transformations.

A quantity of identical, 2 cm wooden cubes was introduced and students were asked how they could find out how much space each occupied and to complete the calculation. This was not a difficult task for most as they had recently completed arithmetical units devoted to the concept of volume, and its calculation for regular objects. The cubes were numbered so that children could follow any positional changes, and eight of them were assembled into a regular structure four cubes in height. Construction was a cube at a time, emphasizing the volume [8 cm^3] of each cube, and recording an updated total volume. Several shape transformations were then carried out, attention being drawn in each case to the correspondence, in volume terms, between what was removed from the initial structure and what was added to make the new one. Each move was easily followed via the numbers on the cubes*, allowing the independence of shape and volume to be consistently and frequently affirmed. The logic of the argument was reiterated for plasticine [a continuous substance], and it was drawn to students' attention that many of them had previously asserted that changing the shape of a piece of plasticine also changed its volume.

The relation of object to displacement volume was introduced via a set of 18 matchboxes and an open plywood box, which was an exact fit for any nine of them. The volume of a matchbox was calculated from approximate measurements, and recorded. The matchboxes were then weighed, and it was 'discovered' that nine of them were full of concrete, while the other nine were 'empty'. One at a time, the light matchboxes were packed into the plywood box, each time asking what had happened to some of the air in the box, and then what volume of it had been displaced [spilled out]. A tally was kept of total volume of the boxes and total volume of the air displaced, emphasizing the correspondence. The packing and recording were repeated for the heavy boxes, emphasizing the correspondence between volume of the displacing object and volume of the displaced air, and the independence of the latter from object weight. The question of substituting water for air in the container was posed and the difference between floating and sinking was raised. This difference was also demonstrated using a bottle containing variable amounts of sand and a measuring cylinder part-filled with water. It was emphasized that *if the object was totally covered by the fluid* then the volume of water [air] it displaced was equal to the volume of the object. Volume is space occupied.

Co-operative discussion

Two identical bottles were shown to students, one filled with sand, the other part-filled, but still heavy enough to sink in water. The bottles were weighed, their weights compared, and students asked whether, if placed in water, they would displace the same or a different volume of water, and why. Students were not used to arguing with each other in the classroom situation, but most responded readily to more direct questioning, and the teacher [CJD] was able to promote a form of debate by feeding the response of one child to another for comment, or as a question. The 'experiment' was then performed, and explanation of its result requested. Children were next asked to imagine that JAR had jumped into a swimming pool, and had sunk to the bottom. The question was, what volume of water would he displace, and why? What if he curled himself into a tight ball? What if he were swimming about under water? The 'debate' was ended when students appeared to have reached consensus, and the lesson concluded with a summary of major points. Time taken was approximately 25 minutes.

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* Piaget (1979 pp. 21–22) found that drawing childrens' attention to actions inducing correspondences is particularly effective in promoting their construction of reversibility, which involves an appreciation of both commutability and vicariance.

OW/NW strategy

Each of the major identified misconceptions of weight, shape, and amount of an object used by students as possible explanations, hence indicators, of the volume of water an object would displace if totally immersed, were recalled and their meanings were clarified*. Three identical glass jars were then introduced, each containing a different weight of material as was shown on the scales. Displacement volume was reintroduced as space occupied, weight was labelled as an 'old way' of measuring/ predicting this and object volume labelled a 'new way'. Five students were then asked, independently, to predict relative displacements of the three jars, first using the 'old way' then the 'new way'. Predictions were recorded and the experiment performed, confirming the 'new way' as correct. Shape and amount, separately, [as old ways] and object volume [as a new way] were taken through the same kind of sequence. Finally, students were required to use the 'new way' exclusively, and were repeatedly confronted by the equivalence of object and displacement volumes as interchangeable measures of space occupied. Thus a book was measured, its volume calculated, and that volume used to predict its displacement if it were to be immersed. The book was followed by an orange, several randomly shaped pieces of plasticine, separately then collectively, and several large, flat metal rings. In each of these latter cases displacement volume was determined and used as a measure of object volume. The lesson given to class C [by HL] took approximately 40 minutes. A more extended version was given to class B [by HL] as the total teaching sequence took an hour.

Results

Testing took place five weeks after teaching, and without prior warning. First, students were shown four objects, three cubes and a stone, and were given their volumes and weights. Two of the cubes were equal in volume but different in weight. The heavier of these cubes was equal in weight to the third cube, but was smaller. The volume of the stone was intermediate between the cubes, but was the heaviest object. Students were asked to order the objects in three ways; in terms of increasing volume, weight, and volume of water each would displace if totally immersed, and to explain the basis for the last ordering. For the second part of the test, students were shown three objects; a regularly shaped paper weight, an irregularly shaped piece of blue putty, and a piece of plexiglass that had rounded edges and corners, and were asked how they would find the weight, volume, and displacement of each.

For class B [OW/NW only], only 1 of the 16 with pretest misconceptions gave evidence in question 2 that object and displacement volume were now simply different procedures for measuring the same construct [we shall call this a category 1 change]. Two more students correctly answered question 1, providing the displacement volume order and giving 'passable' object volume explanations of it [category 2 change].

* In order to deal with the concept, 'amount' was identified with number of 'units', to demonstrate that it is not usually a direct measure of volume. Examples used included amount of money in cents, as opposed to the space occupied by the coins; and the number of building blocks, again as opposed to the space occupied.

For class A [better theory + co-operative discussion] 7 of 19 students were category 1 changes, and a further three were category 2 changes.

For class C [better theory + OW/NW], 11 of 15 were category 1 changes, and one other student was a category 2 change.

Discussion

We chose to allow each teacher to use lesson time deemed appropriate to the strategy concerned, thus typifying the natural situation, consequently time on task differed between classes [A = 55 min, B = 60 min, C = 70 min]. Subsequent experimentation may wish to control this factor more closely, although we doubt that 'a bit more of the same' would change the situation markedly.

As anticipated, OW/NW alone resulted in very few changes in misconceptions and we shall not discuss it further. Our particular interest is the difference in efficacy of OW/NW in comparison with co-operative debate, following teaching of the better theory. Theoretically, as discussed, both strategies may be expected to result in individual knowledge change. What has been illustrated here, however, is a striking additional effect achieved by requiring students to go through the sequence of mental actions needed for the equilibratory replacement of their misconceptions.

There are two final points that we wish to make. First, the class use of OW/NW is a pale approximation of its use with individuals, indicating its remedial potential. Second, although 'one swallow does not make a summer', and further testing is essential, the theoretical basis for OW/NW gives us confidence in predicting wider applicability of the strategy to changing other misconceptions.

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