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Jan H. Van Driel & Nico Verloop

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Teachers' knowledge of models and modelling in science

Jan H. Van Driel and Nico Verloop, ICLON Graduate School of Education, Leiden University, The Netherlands; e-mail: driel@iclon.leidenuniv.nl

This study investigated the knowledge that experienced science teachers have of models and modelling in science in the context of a school curriculum innovation project in which the role and the nature of models and modelling in science are emphasized. The subjects in this study were teachers of biology, chemistry and physics preparing for the curriculum innovation. Two instruments were used: a questionnaire with seven open items on models and modelling, which was completed by 15 teachers, and a questionnaire consisting of 32 items on a Likert-type scale $(n = 71)$. Results indicated that the teachers shared the same general definition of models. However, the teachers' content knowledge of models and modelling proved to be limited and diverse. A group of teachers who displayed more pronounced knowledge appeared to have integrated elements of both a positivist and a social constructivist epistemological orientation in their practical knowledge. Implications for the design of teacher education interventions are discussed.

Introduction

Models play a central role in science education. Usually, the focus is on the content of the models being taught and learned. Yet the nature of the models is not always explicitly discussed. Moreover, in spite of the current emphasis on constructivist teaching strategies, it seems to be unusual to invite the students to actively construct and revise models. Instead, teachers usually present the models to be learned as static facts. However, a new Dutch curriculum innovation project was recently initiated which is aimed at, among other things, focusing more attention on the role and the nature of models and modelling in science. In this context, the knowledge and beliefs science teachers hold about models and modelling are of crucial importance, since they will influence the teachers' perception of the curriculum innovation project, and, ultimately, the way they will implement the innovation.

The study in this paper was carried out in the context of this innovation project. The theoretical framework of the study draws upon the concept of teachers' practical knowledge or craft knowledge. Practical knowledge consists of the accumulated and integrated set of knowledge and beliefs teachers develop with respect to their teaching practice (Grimmett and MacKinnon 1992). Teachers' practical knowledge is derived from teaching experience and formal education, and is ready to be used in their own practice (Beijaard and Verloop 1996). As it is assumed to be the dominant factor in guiding the teacher's behaviour (Verloop

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1992), the personal practical knowledge of teachers exerts a major influence on the way they respond to a new curriculum (Duffee and Aikenhead 1992).

The rationale of this study is connected to one of the aims of the curriculum innovation project, that is, to shift the focus of attention in science teaching from the content to the nature of scientific models. In this respect, teachers' practical knowledge of models and modelling in science is important. Thus, the focus in this study was on investigating the knowledge of experienced science teachers in this domain.

Models in science and in science education

Models and modelling in science

Models in science differ in terms of physical appearance and cover a large range of applications. Several categorizations of scientific models have been described (e.g. Black 1962, J. K. Gilbert 1994), dividing models in terms of appearance (e.g. physical models and mathematical models) or functions. From the latter perspective, models may be characterized as descriptive, explanatory, or predictive. A descriptive model is characterized by a large degree of `positive analogy' between model and target (Hesse 1966). An example is the heliocentric model, describing the orbits of the planets in our solar system. Through the implementation of a theory, an explanatory model may be designed. In the example, the concept of gravity, derived from Newtonian theory, may be used to design a model which explains the movements of the planets. Moreover, the inclusion of theoretical notions in a model enables the formulation of predictions. For instance, Adams and Le Verier could predict the existence of the eighth planet, Uranus, on the basis of a model which included the concept of gravity. Shortly after this prediction was made, Uranus was indeed identified by observation.

Categorizing models serves to emphasize the differences between scientific models. Yet these models share several common characteristics. Instead of presenting a general definition of a scientific model, some authors have tried to identify the common characteristics which apply to all scientific models (De Vos 1985, Van Hoeve-Brouwer 1996).

(1) A model is always related to a target, which is represented by the model. The term `target' refers to either a system, an object, a phenomenon or a process.

(2) A model is a research tool which is used to obtain information about a target which cannot be observed or measured directly (e.g. an atom, a dinosaur, a black hole). Thus, a scale model, that is, an exact copy of an object (e.g. a house, a bridge) on another scale, is not considered to be a *scientific* model.

(3) A model cannot interact directly with the target it represents. Thus, a photograph or a spectrum does not qualify as a model.

(4) A model bears certain analogies to the target, thus enabling the researcher to derive hypotheses from the model which may be tested while studying the target. Testing these hypotheses produces new information about the target.

(5) A model always differs in certain respects from the target. In general, a model is kept as simple as possible. Dependent on the specific research interests, some aspects of the target are deliberately excluded from the model.
(6) In designing a model, a compromise must be found between the analogies and the differences with the target, allowing the researcher to make specific choices. This process is guided by the research questions.
(7) A model is developed through an iterative process, in which empirical data with respect to the target may lead to a revision of the model, while in a following step the model is tested by further study of the target.

In any case, models play an important role in the *communication* between scientists. Individuals may have a mental model, that is, a personal, private representation of a target. Through speech or writing, a mental model may be expressed by an individual. This expressed model is available for discussion with others. Through comparison and testing of their personal, expressed models, scientists may reach agreement on consensus models. Such models belong to the main products of science (Gilbert *et al.* 1998). The process of construction of consensus models is fundamental to the understanding of scientific progress (Van Oers 1988). As the choice for a specific model depends on the context and the purpose of the research, several consensus models may co-exist with respect to the same target. For example, biochemists and theoretical chemists may use quite different models for the corpuscular structure of water.

Models in science education

Many studies have been conducted on the teaching and learning of the *content* of specific models, for instance, studies on corpuscular models (e.g. De Vos and Verdonk 1987, Harrison and Treagust 1996). Thus far, only a few studies have focused on the process of modelling (e.g. S. W. Gilbert 1991) and on students' conceptions about models and their use in science (Grosslight *et al.* 1991). The students in the latter study often held conceptions that corresponded with a `naïve realist' epistomology. That is, the students usually considered models to be exact copies of reality, albeit on a different scale. However, the older students in this study appeared to understand that models are designed for specific purposes, and that a model may change in the course of time, for instance when new empirical data have been analysed. The functions of models in explaining and predicting observable phenomena were only rarely acknowledged by these students. It appears that, until now, there have been no investigations of teachers' knowledge of models and modelling in science.

Purpose and context of this study

The purpose of this study was twofold. From a theoretical perspective, this study aimed at contributing to a better understanding of specific aspects of the practical knowledge of experienced science teachers, that is, their knowledge concerning models and modelling in science. A practical purpose of this study was to contribute to the design of specific activities and interventions, aimed at developing science teachers' knowledge in this domain.

To understand the context of this study, it is important to know that in The Netherlands, the national curriculum traditionally contains physics, chemistry and biology as separate subjects. With the exception of local, small-scale projects, there is no experience with an integrated approach to teaching science. As of 1998, however, such an approach is being implemented in the national curriculum through the introduction of Public Understanding of Science as a new, separate subject, alongside the traditional disciplines of physics, chemistry and biology (De Vos and Reiding, in press). The new subject has three main objectives: (1) to introduce *every* student to major scientific concepts (i.e. life, matter, biosphere, solar system and the universe); (2) to demonstrate the complex interactions between science, technology and society; and (3) to make students aware of the ways in which scientific knowledge is produced and developed. The emphasis on models and modelling is most apparent within the latter objective.

To illustrate the role of models and modelling in the new subject, some elements of the curriculum are concisely portrayed. In the *Life* domain, for instance, students are asked to design a model for the human immunity system. Reflecting on this assignment, the students are encouraged to discuss questions on the nature and the use of models in general. In the *Solar system and universe* domain, the students compare and discuss several models for the solar system from the history of science, such as Ptolemaeus' geocentric model and Copernicus' heliocentric model. In the *Biosphere* domain, finally, students study the role of predictive models with respect to the greenhouse effect. This study also serves to illustrate the role of simultaneous models (Van Hoeve-Brouwer 1996), that is, the use of different models for the same target alongside one another.

The implementation of the new subject is supported by an in-service programme for teachers with teaching experience in either physics, chemistry or biology. This programme was started in 1997 and is conducted on a nation-wide scale. It was decided that the in-service programme should consist of workshops and conferences (60 hours altogether) plus self-regulated study activities, also amounting to approximately 60 hours.

In the present study, the knowledge of experienced science teachers was investigated at the start of this programme in order to ascertain these teachers' practical knowledge as a result of prior education and teaching experience, before specific interventions took place in the in-service programme. Thus, the results of the study could actually inform the design of such activities. Specifically, data were collected in order to map the participants' practical knowledge with respect to models and modelling in science, in terms of the common characteristics of models (see above), the roles, and the functions of models in science.

Design of the study

Two instruments were designed to investigate teachers' knowledge of models and modelling in science. The first instrument was a questionnaire with seven open items, while the other instrument consisted of a Likert-type scale questionnaire.

Open-item questionnaire

The design of the questionnaire was inspired by an instrument developed by Grosslight *et al.* (1991). The questionnaire used in the present study addressed the same themes, namely: (1) types of representations of models; (2) goals and functions of models in science; (3) characteristics of scientific models; and (4) modelling in science, that is, the design and revision of models. The questionnaire consisted of seven open items. The first item addressed the first theme, i.e. the respresentations of models. The respondents were presented with seven specific examples, including a toy car, a picture of a house, Ohm's law, and a water molecule. They were asked to indicate whether they considered each example a model, and why. The six other items addressed the remaining three themes, each theme being covered by two questions. For example, one item was `How would you describe what a model is to someone who is not familiar with models?' (theme (3)).

The questionnaire was administered to a group of teachers $(n = 15)$ at the start of the in-service programme, to be completed by them individually at home. With two exceptions, all of them had more than five years teaching experience in physics, chemistry or biology. No information about models in science was given to them in advance.

The teachers' written answers were analysed applying an interpretative phenomenological approach (Smith *et al.* 1995). First, the answers of every individual teacher were interpreted in terms of the themes mentioned above. Next, it was investigated within every theme whether the teachers' answers could be categorized. For every theme, global descriptions of categories were used as a starting point (e.g. `describing' and `explaining' for theme (2), and the common characteristics mentioned above for theme (3)). Comparing the teachers' formulations with these global descriptions resulted in a more detailed description of the categories. After the categorization of the teachers' answers, an attempt was made to identify the existence of specific patterns in these answers. It was explored whether the teachers' answers within a certain category were related to their answers in other specific categories.

Likert-type scale questionnaire

The four themes that inspired the design of the open-item questionnaire were also used as the starting point for the development of the Likert-type scale questionnaire. Initially, 8 to 12 statements about models and modelling in science were formulated for each theme (e.g. `a model is a simplified reproduction of reality'). Two fellow researchers were asked to comment upon these statements. This resulted in the rejection of five statements, and changes in the formulation of almost every other statement. The final set of statements consisted of 32 items, distributed among the respective themes as follows: (1) types of representation: 5; (2) goals and functions: 8; (3) characteristics: 9, and (4) design and development: 10. Respondents were asked to indicate to what extent each statement was valid for models and modelling in science, using a four-point scale ranging from: (1) `never', through; (2) `sometimes'; and (3) `usually', to (4): `always'. Finally, the respondents were asked to indicate their gender, their number of years of teaching experience, and the subject in which they taught the most hours (either chemistry, biology, or physics).

This questionnaire was administered to a group of science teachers $(n = 71)$, again at the start of the in-service programme and to be completed by them individually at home. This group did not include teachers who had previously completed the open-item questionnaire. This choice was made to avoid possible effects of testing. Given the similarities between the two instruments, teachers' answers to the Likert-type scale questionnaire otherwise might have been influenced by their previously answering the open-item questionnaire. The majority of the respondents were male (80%). The average number of years of teaching experience was 17.5 (standard deviation: 7.5 years). More than a quarter (27%) of the respondents were physics teachers, 35% had a background in biology and 37% taught chemistry (1% unknown).

The analysis of the data included several statistical procedures. After the usual descriptive statistics (frequencies, mean scores, and standard deviations) had been obtained, principal components analyses with varimax rotation were performed. This resulted in the extraction of three factors. These factors were subsequently treated as scales, and subjected to the analyses of reliability. Moreover, Pearson correlations, both within and between scales, were computed. Next, analyses of variance (ANOVA) were performed to investigate whether teachers' scores on the three scales and on the individual items differed significantly with respect to subject and teaching experience. For the latter purpose, the teachers were divided into four groups of roughly equal sizes, that is, (1): less than 10 years, (2): 11-15 years, (3): 16-20 years, and (4): more than 20 years. Levene statistics were incorporated to test for homogeneity of variances, as well as Tukey HSD (*h*onest *s*ignificant *d*ifference) tests for multiple comparisons. Finally, a hierarchical cluster analysis was carried out on the group respondents as a whole to explore whether they could be divided into homogeneous subgroups with distinctive knowledge of models and modelling in science. Squared Euclidian distances were calculated as a measure of distance, and average linkage between groups was applied as a clustering method. This analysis was followed by a series of T-tests, incorporating Levene's test for equality of variances, to explore differences in scores on scales and individual items between groups of respondents. Ultimately, analyses of crosstabs were performed to check whether the teachers were distributed evenly over clusters with respect to subject and teaching experience. All statistical analyses were performed using SPSS, version 7.5.

Results

Open-item questionnaire on models and modelling

All the teachers produced a general description of a model. These descriptions appeared to be very similar and could be summarized as follows: `A model is a simplified or schematic representation of reality.' Specific results, however, indicated a large degree of variety of the teachers' knowledge of models and modelling in science. This variety became apparent when the teachers' answers were analysed per theme:

(1) The teachers held different beliefs with respect to the *representational modes* of scientific models. When asked to respond to seven specific

examples, one teacher classified all these, including a picture of a house and a toy car, as a model, referring to each example's potential to represent specific aspects of reality. On the other hand, other teachers rejected almost all the examples, including a molecule of water. In the view of these teachers, explanatory potential appeared to be an important criterion for an example to qualify as a model.

(2) The teachers emphasized different *functions* of models. Specifically, the explanatory function and the descriptive function of models were stressed. However, some important functions (e.g. using models to make predictions) were rarely mentioned. Three teachers discussed the exemplary function of models, which does not seem appropriate within the context of science. Teachers emphasizing the explanatory function would normally accept only a few of the given examples as models (see point 1), whereas teachers stressing the descriptive function seemed to accept most of the examples mentioned above as scientific models.

(3) The teachers mentioned different *characteristics* of models. All the teachers mentioned the relation between model and target (first characteristic; see above). Three of the teachers only mentioned this aspect. Others, however, mentioned five to six of the seven characteristics listed earlier. The latter group was expected to have rejected most of the examples of models presented earlier, arguing that these examples would not comply with all the characteristics. No relation could be found, however, between the number of characteristics the teachers mentioned, and the number of examples (see point 1) they classified as models.

(4) Differences between the teachers' epistemological orientation became apparent from their answers to questions about *modelling in science* (i.e. designing and revising models). Most of the teachers displayed a constructivist orientation, indicating, for instance, that different models can co-exist for the same target, dependent on the researchers' interest or theoretical point of view. A minority of the teachers, however, reasoned in termed of logical postivism. These teachers stated that a model should always be as close to reality as possible and that a model may become `outdated' when new data are obtained. However, it was not possible to identify relations between the teachers' epistemological orientations and the other themes discussed above.

Likert-type scale questionnaire

Mean values for individual items varied from 1.65 to 3.39, whereas standard deviations ranged between 0.32 and 1.01. The highest number of missing values was four for one item. All 32 items were thus entered in principal components analyses with varimax rotation. These analyses resulted in the extraction of three factors. Eleven items had high loadings (>0.40) on Factor 1, eight items loaded similarly high on Factor 2 and another eight items on Factor 3. Five items remained that had low loadings (<0.25) on all three factors. These items were not used during further analyses.

Cronbach alpha values of the three scales constructed in correspondence with the factor solution were 0.75 (Factor 1: 11 items), 0.67 (Factor 2: 8 items), and 0.64 (Factor 3: 8 items). Given the numbers of items per scale, plus the fact that the questionnaire was administered for the first time, these Cronbach alpha values may be considered acceptable (Pedhazur and Pedhazur Schmelkin 1991: 109-10). On the basis of the analysis of item-total statistics, it was concluded that no items had to be removed from one of the three scales: not a single case of elimination of items resulted in the rise of the Cronbach alpha. Moreover, all the Pearson correlations of individual items with their respective scales were significant at the 0.001 level (2 tailed). The values of these correlations ranged between 0.42 and 0.69. Next, the respondents' scores on a scale were divided by the number of items per scale. For every scale, mean scores and standard deviations were then calculated.

The interpretation of the scales identified in the process described above revealed three distinctive aspects of models and modelling in science. The first scale grouped statements referring to the relations between models and targets in a positivist way. These statements scored relatively high $(M = 2.99, SD = 0.40)$, indicating that, in general, the respondents would support the idea that a model is a simplified reproduction of reality, whose most important function is to enable causal explanations of phenomena. Moreover, a high score on this scale is indicative of the belief that the development of models is a straightforward, rational process.

The items with high loadings on the second scale referred to the physical appearance of models. These items had in common that they concerned the manner in which models are represented, through the use of drawings, pictures, analogies, or scale models. The mean score for this scale was 2.21 $(SD = 0.35)$, suggesting that the respondents allotted a large variety of representational modes to scientific models. For example, 63% of the respondents believed that `sometimes' even a photograph can be a model.

The third scale grouped items that referred to the use and the construction of models in a social context. Characteristic of these items was the recognition of the idea that models are the products of human thought, creativity and communication. The statement with the highest loading on this factor (0.66), read `A model depicts the ideas of scientists'. The mean score of this scale was 2.76 $(SD = 0.38)$. In particular, statements referring to the role of creativity $(M = 3.24)$, and questions posed by the researcher $(M = 3.30)$ with respect to developing models received strong support. Table 1 presents the scales and sample items.

Pearson correlations between the three scales were calculated, which identified a significant correlation (0.33, significant at the 0.01 level: 2-tailed) only between the first and the third scale. This indicates a tendency among the respondents to combine the notion that a model is a simplified reproduction of reality with the idea that models are used and constructed in a social context.

The analyses of variance revealed that the teachers' scores on the three scales did not differ significantly with respect to years of teaching experience. With respect to the subject the teachers taught, however, a significant difference emerged. Specifically, the teachers of chemistry scored higher than the physics teachers on the first scale, relating models and targets in a positivist fashion $(M = 3.15$ and 2.80, respectively, $p < 0.05$; for biology teachers M was 2.96). The teachers' subject accounted for 12% of the observed variance in the respondents' scores on this scale. For a better understanding of this difference, multiple comparisons were performed at the item level, focusing on the 11 items of which

Table 1. Scales within the Likert-type scale questionnaire on models and modelling, and sample items.

Scales	*Sample scale-items*
Relating models and targets	`A model is a simplified reproduction of reality' `A model corresponds with the target as much as possible' `One attempts to keep a model as simple as possible' `In the course of its development, the correspondence between a model and its target is increased'
Physical appearance of models	`A model has the shape of a drawing' `Analogies are used in the development of models' `The most important difference between a model and the target concerns the scale'
Social context of models	`The development of a model is guided by the questions of the researcher' `A model depicts the ideas of scientists' `Creativity is a major factor in the development of models'

this scale consisted. The analysis showed, that the chemistry teachers scored significantly higher $(p < 0.05)$ than the physics teachers on two items:

(1) The assessment of models focuses on truth, rather than usefulness;
(2) Scientists use the most advanced models available.

Mean scores for chemistry teachers on these items were (1): 2.48 and (2): 2.85, whereas the physics teachers' mean scores were (1): 1.84 and (2): 2.37. These results indicate that the chemistry teachers were more strongly committed to logical positivism than the physics teachers, whereas the biology teachers held an intermediate position.

Out of the sample of 71 respondents, 59 appeared to have completed all 27 items comprising the three scales. These 59 respondents were entered in a hierarchical cluster analysis. On inspection of the squared Euclidean distance coefficients, a five-cluster solution was chosen. The increase in the value of this distance measure was relatively large from a five-cluster to a four-cluster solution (Norušis/SPSS Inc. 1992). The respondents were distributed among these five clusters as follows: 37 were classified as cluster 1; 19 were grouped together in cluster 2; whereas the remaining three were assigned one each to clusters 3, 4 and 5. These latter clusters were not used in further analyses. The interpretation of clusters 1 and 2 is discussed below.

Clusters 1 and 2 were entered in a series of T-tests to explore whether they scored differently with respect to the three scales, and with respect to individual items. It appeared that cluster 2 $(n = 19)$ scored significantly higher $(p < 0.001)$ than cluster 1 $(n = 37)$ on scales (1), relating models and targets, and (3), social context of models, and significantly lower $(p < 0.05)$ on scale (2), physical appearance of models. These results are summarized in table 2. For this table, the respondents' scores on a scale were divided by the number of items per scale. Then, mean scores (M) and standard deviations (SD) were calculated. T-tests at the item level revealed that cluster 2 scored significantly higher than cluster 1 on almost every individual item belonging to scales (1) and (3), the differences of the

Table 2. Scores of clusters 1 and 2 on the three scales: means (M), standard deviations (SD) and differences between the means (Diff. means).

Scales	*Cluster*	*M*	*SD*	*Diff. means*
Relating models and targets	1 $(n = 37)$	2.82	0.29	−0.53***
(11 items)	2 $(n = 19)$	3.35	0.26	
Physical appearance of models	1 $(n = 37)$	2.25	0.27	0.18*
(8 items)	2 $(n = 19)$	2.07	0.34	
Social context of models	1 $(n = 37)$	2.63	0.28	−0.51***
(8 items)	2 $(n = 19)$	3.14	0.24	

Notes: * The difference of the means is significant at the 0.05 level (T-test; 2-tailed).
*** The difference of the means is significant at the 0.001 level (T-test; 2-tailed).

item means ranging between 0.25 and 0.84. The statements with the largest differences of the means were:

(1) The assessment of models focuses on truth, rather than usefulness (0.84); and
(2) Creativity is a major factor in the development of models (0.71).

These results indicate that the teachers in cluster 2 seemed to hold a positivist view of models, on the one hand, while recognizing the idea that models are constructed in a social context, on the other hand. In the next section, this paradoxical finding is discussed in more depth. Moreover, compared with the teachers in cluster 1, their ideas about the ways models are represented are less specific.

Finally, analyses of crosstabs were performed to check whether the teachers were distributed evenly over the two clusters with respect to their subject, and teaching experience. These analyses showed that physics teachers were slightly over-represented in cluster 1 (13 observed, whereas 10 were expected), and that teachers of chemistry were over-represented in cluster 2 (9 observed; 6 expected). However, the results of chi-square tests revealed that these differences between observed and expected frequencies were not significant (> 0.1).

Conclusions

Understanding science teachers' knowledge of models

The results of the present study indicate that experienced science teachers, though they share the general notion that a model is a simplified representation of reality, may have quite different cognitions about models and modelling in science. For instance, the results of the open-item questionnaire revealed a large variation in the criteria the teachers used to determine whether or not specific examples qualified as scientific models. Moreover, from the same questionnaire it appeared that the teachers emphasized different functions and characteristics of models. Some functions and characteristics of models were rarely mentioned by these teachers (e.g. using models to make predictions, or perceiving a model as a tool for obtaining information about a target which is inaccessible for direct observation).

From the Likert-type scale questionnaire, three scales emerged for the characterization of the teachers' knowledge of models and modelling in science. With one exception, the scores on these scales did not differ significantly with respect to the teachers' subject or experience. The only exception concerned the scores of the chemistry teachers as compared with the physics teachers on the scale associated with the relation between models and targets. The results suggested that the chemistry teachers more strongly supported the positivist notions that the quality of a model is determined by the extent of positive correspondence with its target, and that the development of models is a straightforward, rational process. It is unclear whether this difference between teachers of chemistry and physics was associated with their prior education or with teaching experience in their respective subjects.

On the whole, the results of this study indicate that the knowledge of the majority of the teachers of models and modelling in science was not very pronounced. For instance, the mean scores of the teachers in cluster 1 (see above), who constituted two-thirds of the respondents to the Likert-type scale questionnaire, ranged between `2' and `3' on all scales. On the other hand, about one third of the teachers (associated with cluster 2) displayed significantly more distinct cognitions with respect to models and modelling, scoring either higher (>3.0) or lower (<2.1) on the three scales. The alternation between high and low scores suggests that this subgroup held particular ideas with respect to all scales. As stated previously, this difference in knowledge between the two subgroups appeared *not* to be related to the teachers' subject or experience.

Interestingly, the teachers in cluster 2 scored high on two scales, that is, scale (1), relating models and targets, and scale (3), social context of models. These scales appeared to be significantly correlated. A high score on scale (1) is considered to be indicative of a strong commitment to logical positivism, whereas a high score on scale (3) is in support of the notion that models are used and developed in a social context. The latter notion may be associated with a (social) constructivist epistemology. Thus, one may conclude that the knowledge of the teachers in cluster 2 is internally inconsistent. From a practical knowledge perspective, however, this result may be explained as follows. As practical knowledge is often `tacit' or implicit, these teachers may have integrated different perspectives about models and modelling in science in their conceptual frameworks, or `functional paradigms' (Lantz and Kass 1987), thus resulting in inconsistencies of which they are not aware. Possibly, their high scores on scale (1) are related to their prior, disciplinary education, whereas the social constructivist notion has been added due to the influence of the recent educational literature. Anyway, we are not suggesting that a high score on either scale is indicative of an epistemological misconception. One could even argue that the teachers in cluster 2, more or less implicitly, combine `the best' of two orientations.

Implications for the design of interventions

This study makes it clear that teachers' knowledge of models and modelling in science is often limited, and may include inconsistencies. To extend science teachers' knowledge in this domain, they could, of course, be provided with specific information and relevant literature. Specific activities may be designed, however, to deal more effectively with respect to developing the teachers' practical knowledge. For instance, teachers may be asked to discuss specific examples with each other, focusing on the reasons why they consider an example to be a model or not. Such discussions may facilitate the identification of common characteristics of scientific models. Moreover, teachers may be asked to analyse models in textbooks from various domains within science with respect to these models' functions and characteristics. In particular, the predictive function of models should be emphasized, as this function appeared to be underexposed in the teachers' cognitions. In the context of the innovation project focused on in the present study, the predictive function is particularly important when models of the biosphere are the focus of attention. In addition, teachers could focus on a specific target and analyse different models and their development throughout the history of science with respect to this target. Through this analysis, the role of creativity and other aspects of the social context of models may be illuminated.

Specific activities may be designed to anticipate teachers' epistemological orientations. For example, the co-existence of various models of the same target may be analysed to demonstrate that a model does not necessarily bear as much positive correspondence to a target as it possibly could. Many physical and chemical phenomena, for instance, can be adequately explained with a `simple' stick-and-ball model to represent moecules, in preference to a more advanced model, incorporating quantum mechanics. Such examples may promote the teachers' understanding of the role of the questions or the purposes of the researchers in relation to the choice or the design of a model. Specifically, the limitations of a model, and the deliberate inclusion in a model of differences between this model and its target, should receive attention. In addition, discussing their analyses of these, and other, examples with each other may contribute to teachers becoming aware of possible inconsistencies in their knowledge of models and modelling in science.

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