8 HOW YEAR 7 TO YEAR 10 STUDENTS CATEGORISE MODELS: MOVING TOWARDS A STUDENT-BASED TYPOLOGY OF BIOLOGICAL MODELS

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Abstract

The present study aims to provide a typology of biological models which is based on students' perspectives and which, therefore, might be useful for researchers and practitioners in science education. Based on the repertory grid technique, students (*N*=19) were asked to categorise model-triads by communicating both the similarity between two models and the way in which the third model differed from these. Each identified perspective was analysed and transformed into an item by formulating a short sentence describing the perspective. Within a quantitative approach (*N*=725), these items could be summarised as four factors ('replication', 'illustration', 'explanation', and 'prediction') which served as criteria to classify 16 biological models. Using this data, a cluster analysis of the 16 biological models (as cases) created three types of biological models: 'iconic models' (mainly three-dimensional, material models), 'explanatory models' (mainly diagrams and drawings), and 'strange models' (a non-homogenous cluster including, e.g., a model organism). Based on the findings it is recommended, e.g., to consider different types of models when assessing students' understanding of models and modelling in science education research and that each model-type has its own value when discussing models in biology classes.

Keywords: biological models, classification, typology

1. Introduction

The importance of models for scientific enquiry (e.g. Frigg & Hartmann, 2006; Harré, 1970) and science education (e.g. Gilbert & Boulter, 1998; Gilbert, Boulter, & Elmer, 2000; Oh & Oh, 2011) is recognised in the literature. As a basis for theoretical reflections about models in science (e.g. Harré, 1970) as well as in science education (e.g. Boulter & Buckley, 2000), several model classifications have been proposed in literature. For example, Harré (1970) argues that some kinds of models are used to explain things or processes that are already known, whereas other kinds of models are used to develop new (hypothetical) knowledge regarding a certain phenomenon. In science education, model classifications might be used as a theoretical framework for the selection of teaching contexts as they might 'alert teachers and writers to the conceptual demands of the different model[s]' (Harrison & Treagust, 2000, 1014). However, there are a number of different model classifications which are based on different criteria and therefore provide different classes or types of models (e.g. Boulter & Buckley, 2000; Buckley, Boulter, & Gilbert, 1997; Harrison & Treagust, 2000). Hence, it is difficult for researchers and practitioners in science education to decide which classification to use as theoretical framework. Furthermore, it is argued that students' perception of models is likely to differ from experts' point of view (Harrison & Treagust, 2000). Therefore, the present study aims to provide a classification of biological models which is based on students' criteria and might therefore be useful for science teaching and research in science education.

2. Theoretical background

2.1 Concerning the notion of classification and typology

According to Bailey (1994), the term *classification* can be seen as the sorting of objects based on their similarity using one single criterion. Furthermore, a classification should be exhaustive and exclusive. In comparison, the term *typology* is used for a multidimensional and conceptual classification: Objects are classified using more than one criterion, resulting in various *type concepts* which are not necessarily empirical cases (Bailey, 1994; Capecchi, 1968). The key issue of classifications and typologies is the selection of criteria because all classifications and typologies depend on the respective criteria (Bailey, 1994).

2.2 Classifications of biological models

There are different model-classifications in literature which may be distinguished due to the criterion they use to classify models. A *semantic* classification of models refers to their representational function (Frigg & Hartmann, 2006). One semantic classification is provided by Frigg and Hartmann (2006) who distinguish between representational models and models of theory. While the former represent 'a part of the world' (741), the latter are said to be a structure which satisfies all propositions of a theory.

An *ontological* classification of models points out the fact that the model object can differ in itself, i.e. that a model can have different modes of representation (Boulter & Buckley, 2000).

For example, Boulter and Buckley (2000) put forward concrete models (i.e. material models), verbal models, visual models, mathematical models, and gestural models. The authors emphasise that there are many models which are composites of more than one mode of representation.

According to the *epistemology* it is possible to distinguish models based on their role in the process of model development. In accordance with Gilbert et al. (2000), there are primarily mental models, expressed models, scientific models, historical models, and teaching models.

3. Research questions

The aim of this research is to develop prominent perspectives which are used by students to classify biological models and to distinguish different *type concepts* of models based on these perspectives. Two research questions are addressed:

1. Which perspectives are used by students to classify biological models?
2. To what extent is it possible to develop different *type concepts* of models based on students' perspectives?

4. Method

The research was based on the repertory grid technique (Kelly, 1955). The repertory grid technique uses a two-step approach to elicit the perspectives ('constructs'; Kelly, 1955) which are used by subjects to structure their surroundings (Fransella & Bannister, 1977): First, several elements (e.g. biological models) are presented to respondents to elicit their personal constructs. Secondly, respondents characterise all elements by using the elicited constructs. Kelly (1955) emphasises that a selection of the elicited constructs can be used in the second step.

In this research the *development of perspectives* was performed qualitatively (N=19; students from secondary school; 12 to 17 years old; school year 7 to 10; from Berlin, Germany). The *characterisation of elements* was carried out quantitatively based on a larger sample (N=725; students from secondary school; 11 to 18 years old; school year 7 to 10; from Berlin).

4.1 Developing perspectives

We selected 28 elements (i.e. pictures as representations of biological models; cf. Appendix) which cover different kinds of models as described in literature (e.g. Boulter & Buckley, 2000; Harrison & Treagust, 2000). The models were presented to students from Berlin (Germany) in triads and randomly drawn out of this pool of the 28 models. Ten triads were consecutively presented to each student. To complete the tenth triad two randomly selected models were used for a second time. On each occasion the students were requested to select two models that are alike and to separate these from the third model. Furthermore the students had to name the criteria they referred to when arranging the models (construct and contrast pole; Kelly, 1955). The interviews were recorded and the mentioned constructs and contrast poles were noted during the interviews.

The constructs were analysed and deductively coded based on existing perspectives (Mayring, 2000). As a starting point, the coding agenda of Meisert (2008) was used since it was developed inductively based on students' responses and should therefore be applicable to analyse students' constructs. However, Meisert (2008) asked her respondents whether or not something is a model and therefore restrained the students' answers a priori to this point of view. Consequently, it was predictable that new perspectives would be found.

4.2 Characterising biological models

The identified perspectives were transformed into 15 statements and a four point rating scale was added (not at all – hardly – mainly – totally). Due to economic reasons, 16 of the 28 models were selected, resulting in 16 models (cf. Appendix) each to be characterised using the 15 statements (cf. Table 2). A balanced incomplete block design with t=16, b=30, r=15, k=8, and λ=7 was developed to reduce the number of models to be characterised for each student from 16 to eight (Giesbrecht & Gumpertz, 2004).

For the purpose of data reduction, an exploratory factor analysis was performed using the complete data (i.e. regardless of which model had been characterised). This resulted in a plausible four factor solution. Therefore, the 15 statements were converted into four factors.

The mean score in the four factors was calculated for all 16 models. A cluster analysis including the 16 models as cases characterised by the four mean scores was undertaken to develop *type concepts* of models with homogenous mean scores within the four factors.

5. Results

5.1 Developing criteria

As suggested by Kelly (1955) not all elicited constructs were selected for the characterisation of models. Especially, constructs which referred to the models' modes of representation or to the corresponding original were excluded because minimal variance was expected. According to the *mode of representation* the students used diverse criteria to categorise the models. For example, some students set model organisms apart from diagrams, while others distinguished between dynamic and static models. The perspective *original* was used to compare the models due to their subject (Harré, 1970).

Table 1 shows the 15 selected perspectives and the corresponding statements. Some students described models as *real models*. The students most often referred to semantic perspectives when categorising the models. Several students mentioned that the model was smaller or bigger than the original (*size*), that the model was a *simplification*, or that there were *differences* between the model and the original. Students described models which showed *assumptions* and some which showed *knowledge*. Models which represented a *process* or a *relation* were also described. Epistemologically, the students categorised the models based on their use *to depict*, *to focus* on, *to explain*, or – more generally – *to find out* new things about the original. The suitability of models for *school* was identified for different reasons but especially because of the models' size or complexity. Finally, none of the interviewed students categorised the models by referring to the use of models in developing *hypotheses*. This perspective has been described by Meisert (2008) and is also an important feature of models in theoretical literature (cf. Krell, Upmeier zu Belzen, & Krüger, 2012; Oh & Oh, 2011). A statement describing this perspective was therefore added (Table 1).

Table 1. The perspectives used by the students to categorise the 28 biological models

	Perspective	Statement
OT	real model	*To what extent do you agree that this is a model?*
semantic perspectives	size	*This model shows [the original] in a smaller or bigger size.*
	simplification	*This model is a simplification of [the original].*
	differences	*This model is different from [the original].*
	assumptions	*This model shows what is assumed about [the original].*
	knowledge	*This model shows what is known about [the original].*
	process	*This model demonstrates processes within [the original].*
	relation	*This model demonstrates relations within [the original].*
	replication	*This model looks like [the original].*
epistemological perspectives	to depict	*The model is used to depict [the original].*
	to focus	*This model is used to represent specific characteristics of [the original].*
	to explain	*This model is used to explain [the original].*
	for school	*The model is suitable for school.*
	to find out	*This model is used to find out new things about [the original].*
	to hypothesise#	*This model is used to develop assumptions about [the original].*

Note. The statements were translated from German by the authors. OT: Ontological Perspective. #: This perspective was added because of its theoretical importance.

5.2 Characterising Biological Models

In summary, each student characterised eight models based on the 15 statements (Table 1). As the factor analysis was carried out for the complete data (i.e. regardless which model was characterised) it was finally done based on N=5,575 characterisations. A principal component analysis of the data with varimax rotation was performed. The overall KMO measure was .88

('great'; Field 2009), for individual items >.71 ('good'). Bartlett's test ($\chi^2(105)=16249.09$; $p<.000$) indicated that correlations between items were sufficiently large. Four factors had eigenvalues of >1 and in sum explained about 55% of the variance. Table 2 shows the factor loadings after rotation, values <.30 are not shown.

Table 2. The results of the factor analysis (N=5,575)

Statement	**Explanation** Factor 1	**Illustration** Factor 2	**Prediction** Factor 3	**Replication** Factor 4
This model is used to explain [the original].	.71			
This model shows what is known about [the original].	.68			
This model shows what is assumed about [the original]	.62			
This model demonstrates relations within [the original].	.62			
This model demonstrates processes within [the original].	.59			
This model is a simplification of [the original].	.33	.63		
To what extent do you agree that this is a model?		.61		
This model shows [the original] in a smaller or bigger size.		.58	.49	
The model is used to depict [the original].	.33	.58		.41
The model is suitable for school.	.39	.54		
This model is used to represent specific characteristics of [the original]	.35	.37	.35	
This model is used to find out new things about [the original].			.74	
This model is used to develop assumptions about [the original].	.41		.65	
This model is different from [the original]. (differences) [#]				.87
This model looks like [the original].		.36	.32	.69
variance (%)	19.27	14.47	10.46	10.17
consistency	α=.74	α=.69	α=.57 (r=.40**)	α=.54 (r=.38**)

Note. Cronbach's α or Pearson's r were used as a measure of consistency. In the questionnaire, the placeholder [the original] was replaced by the respective original. Items which have been selected for each factor are highlighted. [#]: This item was negatively coded for the factor analysis.

The items in each factor suggest naming factor 1 ‘explanation’, factor 2 ‘illustration’, factor 3 ‘prediction’, and factor 4 ‘replication’. The item *to focus* was added to the second factor but it loads relatively high on the first (0.347) and third (0.346) as well.

As mentioned above, models can be classified based on different criteria. Because a classification is a one-dimensional system for the categorisation of objects (Bailey, 1994) each factor may be used as a student-based criterion for classifying the biological models.

For each model the mean scores of the four factors were calculated (Table 3). The results show that the mean score of ‘illustration’ is >2.5 for all models except models M15 and M16 and the mean score of ‘prediction’ is <2.5 for all models except model M12. Regarding the factor ‘replication’, the mean scores are >2.5 for eight models, five of them may be referred to as scale models and three as diagrams (cf. Appendix). The standard deviation indicates that the variance is relatively small for the factor ‘prediction’ (sd=0.14) but larger for the other factors (0.28≤sd≤0.46).

Table 3. The mean scores of the four factors for all 16 models

Model	Explanation	Illustration	Prediction	Replication
(M1) predators and prey (circuit)	3.06	2.86	2.39	2.83
(M2) human arm	2.97	2.94	2.32	2.37
(M3) photosynthesis	2.94	2.57	2.18	2.32
(M4) human mouth	2.92	2.85	2.33	2.05
(M5) biomass	2.84	2.90	2.45	2.44
(M6) predators and prey (curve)	2.82	2.68	2.44	2.61
(M7) crossbreeding	2.79	2.75	2.43	2.64
(M8) dragonfly	2.71	2.97	2.37	2.72
(M9) flower	2.65	3.08	2.36	3.15
(M10) cell membrane	2.57	2.89	2.38	2.78
(M11) *Homo neanderthalensis*	2.50	2.69	2.57	3.14
(M12) palm leaf	2.36	2.81	2.22	2.45
(M13) plant seed	2.29	2.70	2.35	2.68
(M14) environmental disaster	2.52	2.54	2.29	1.80
(M15) human heart (textual model)	2.20	1.77	1.98	1.50
(M16) *Aplysia californica* (organism)	2.17	2.22	2.22	1.96
ms	2.64	2.70	2.33	2.46
sd	0.28	0.32	0.14	0.46

Note. The shades of grey show models in one common cluster (cf. Figure 1).

Unlike a classification, a typology is multidimensional and conceptual (Bailey, 1994). The 16 models were therefore used as cases and the four factors as criteria to develop student-based model *type concepts*. A common method for developing a typology is the cluster analysis (Romesburg, 1984/2004).

The mean scores of the four factors for each model (Table 3) have been analysed in a hierarchical cluster analysis using the Ward algorithm (Romesburg, 1984/2004; Wishart, 2006). The cophenetic correlation (r=.77) indicates a strong match between the clustering tree and the Euclidean distances between the 16 models (Romesburg, 1984/2004). The hierarchical cluster analysis suggests that three clusters represent the data appropriately. The best three cluster solution (Figure 1) was replicated in about 70 % of 1,000,000 trials with random starting conditions ('focal point clustering'; Wishart, 2006).

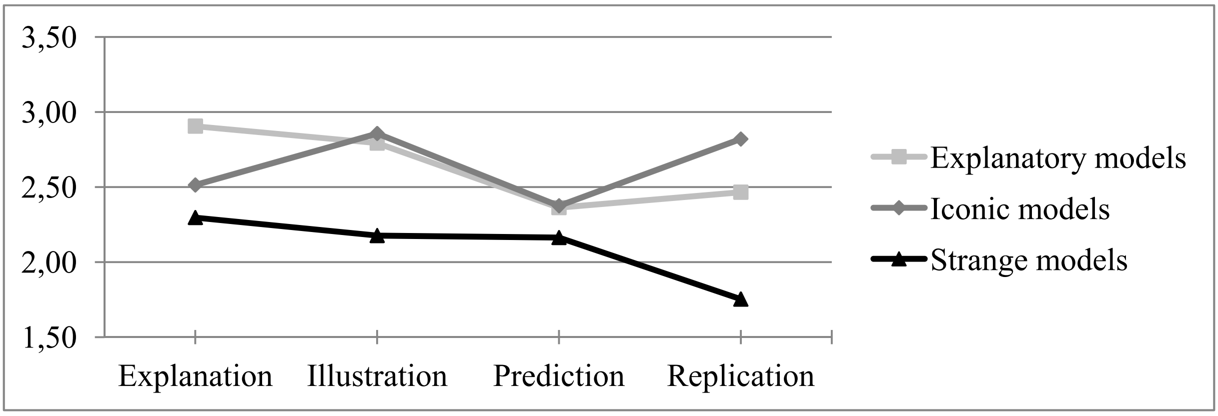

Figure 1. Cluster values in the four factors.

The 'explanatory models' cluster includes models M1 to M7, cluster 'iconic models' covers models M8 to M13, and cluster 'strange models' accounts for models M14 to M16 (cf. Appendix). To highlight the high values of the first two clusters concerning 'explanation' and 'replication', the first cluster was named 'explanatory models' and the second cluster 'iconic models'. Consistently, cluster 'explanatory models' includes models which are somewhat abstract, e.g. diagrams or drawings, and cluster 'iconic models' includes models which represent the outer shape of the original more accurately. The third cluster was called 'strange models' because the mean scores of all factors are <2.5. The three models which belong to this cluster may in fact be seen as strange models from the students' points of view: A model of the population bottleneck (M14), a statement which was included in the survey to illustrate that models do not have to be in the concrete mode (M15), and a model organism (M16).

'Explanatory models' and 'iconic models' only differ significantly in the factors 'explanation' (p<.05; d=1.34) and 'replication' (p<.01; d=2.93). These two clusters can be seen as homogeneous since the standard deviations of the factors within the clusters are smaller than the overall standard deviation of the four factors. Regarding 'strange models' this only applies to 'explanation' and 'replication' but not to 'illustration' and 'prediction'. Furthermore, the cluster 'strange models' has mean scores which are significantly smaller than the mean scores of the other two clusters (p<.05; 1.32≤d). The only exception are the mean scores of 'iconic models' and 'strange models' concerning 'explanation' with p=.12.

6. Discussion

Before discussing the findings, some methodological constraints have to be made. First, the *development of perspectives* was done qualitatively based on a rather small sample (N=19). However, each student got ten model triads and was requested to name construct and contrast pole (Kelly, 1955) each time. Hence, in total, the students were requested to name construct and contrast pole 190 times. Furthermore, an already developed coding scheme was used (Meisert, 2008) and only a few new perspectives were found. However, asking more students may result in additional perspectives. Second, 28 models were selected for the development of criteria and 16 models were characterised in the quantitative step. The models were chosen in such a way that a wide range of different models was covered (cf. Appendix). Buckley et al. (1997) developed a model-typology by analysing different models of the heart and the lunar eclipse which are used in schools. The authors point out:

> The selection of examples from just two phenomena of science education may reduce its [the model-typology's] value. The two phenomena used are of human scale and of much larger scale. The examination of models of phenomena at much smaller and less accessible scale [...] or those that take place over long time spans [...] may result in elaborations or revisions of the categories and criteria we have used (101-102).

In the present study a much wider range of different models was used. But the general argument still remains: Using even more models could result in even more perspectives. However, due to economic reasons as well as the practicability of the study, a constraint had to be made. Nevertheless, further research could take the findings of the present study up and potentially reveal additional model *type concepts*.

The student-based perspectives could be assigned to three broad dimensions which have already been described in literature (Frigg & Hartmann, 2006): *ontology*, *semantic*, and *epistemology*. The epistemological perspective *for school* could not be described clearly because the students saw the models as suitable for school for different reasons, e.g. with reference to the models' sizes or complexities. The dichotomy school model vs. scientific model seems to be important for students' understanding of models. For example, Treagust, Chittleborough, and Mamiala (2002) argue that students' understanding of the nature of models may be more effectively fostered when discussing (abstract) scientific models than when making use of school models. Certainly more research is necessary to shed light on the question of whether primarily ontological perspectives are used by students to decide if a model is seen as suitable for school or not.

The perspective *to hypothesise* was not consulted by the interviewees. In fact, some students explained that a model shows *assumptions*. Since, in these cases, the relationship between the model and the original rather than the enquiry process was in the focus of the students, this perspective was added to the semantic dimension (Table 1). During the interviews, students classified three-dimensional, concrete models as *real models* and set them apart from *model organisms* or *diagrams*, for instance. These results support the findings of others and underline that students seem to associate the term model primarily with concrete entities (e.g. Ingham & Gilbert, 1991). Thus, the diversity of models – including concrete models as well as more abstract entities – is apparently not entirely recognised by students. Consequently, it might not only be important to learn how to model but also to learn models in different modes of representation and to learn about models and modelling (Gilbert & Boulter, 1998).

The overall data was reduced to four factors describing the extent to which a model is seen as 'explanation', 'illustration', 'prediction', or 'replication'. The first three factors reflect different purposes of models as described, e.g., by Krell et al. (2012): describing, explaining, and predicting. Compared to this, the factor 'replication' refers to the model's ontology and reflects the similarity between the model and the original. The three diagrammatical models (M1, M6, and M7) have comparatively high mean scores in this factor, which indicates that students seem to understand diagrams as accurate representations of the respective phenomena (i.e. with a high degree of 'positive analogies'; Hesse, 1966). Consequently, the notion that diagrams are also representations which are highly idealised might be discussed in school. Visual models (M1 to M7) in particular have high values in the factor 'explanation', which seems to hint at the fact that models in this mode of representation (Boulter & Buckley, 2000) are seen as more explanatory than other models by students. The factor 'illustration' has the highest mean score (*ms*=2.70; *sd*=0.32), which shows that the 16 models are mostly seen as an 'illustration' and includes, amongst others, the perspectives *real model*, *to depict*, and *for school*. This may be a hint to students' dominant understanding of models as entities to visualise something in school (Ingham & Gilbert, 1991). Finally, students seem to understand the 'predictive nature of models' (Treagust, Chittleborough, & Mamiala, 2004) only to a relatively small extent (*ms*=2.33; *sd*=0.14) which corresponds with the conclusion of others (e.g. Grosslight, Unger, Jay, & Smith, 1991).

Three clusters were developed by analysing the 16 models' mean scores in the four factors (Figure 1). The two clusters 'explanatory models' and 'iconic models' may be seen as model *type concepts* because they are homogeneous clusters. This is not the case for the 'strange models' cluster. This cluster has mean scores of <2.5 in the four factors, indicating that students do not think that the student-based perspectives when categorising models are applicable to the 'strange models'. This cluster may therefore be an artefact including entities which do not meet the requirements of models from the students' points of view. The cluster 'explanatory models' includes diagrams (e.g. M6) and functional models (e.g. M2) in the visual mode of representation (Boulter & Buckley, 2000). The cluster 'iconic models' includes scale models (e.g. M9) as well as functional models (e.g. M12) which are seen as representations with a high degree of 'positive analogies' (Hesse, 1966) concerning the original's shape. Almost all models (except M10) in this cluster are three-dimensional, material models ('concrete mode' of representation; Boulter & Buckley, 2000).

The two *type concepts* suggest that students might understand some models as being 'iconic' but others may be seen as 'explanatory'. In general, a typology provides researchers in the field of models and modelling in biology education as well as teachers with a student-based classification of biological models which allows them 'to rise above individual, difficult to compare instances and consider them in terms of conceptual categories' (Buckley et al., 1997, 90). Bailey (1994) emphasises: 'Although typologies are often seen as purely descriptive (rather than explanatory) tools, they often provide for the study of relationships and even the specification of hypotheses concerning these relations' (14). Hence, when trying to assess students' understanding of models and modelling (cf. Grosslight et al., 1991; Krell, 2012; Treagust et al. 2002, 2004) one should consider the effect of the respective model (Krell et al., 2012). A reference to only one type of models in questionnaires or interviews (e.g. three-dimensional, material models) may give researchers an insight into students' understanding of this *type concept*. In contrast to such an approach, a broad range of models may be implemented in assessment instruments to analyse the consistency of students' understanding within and between different types of models.

7. Educational implications

Regarding models and modelling, three major educational aims are proposed in literature. Students should learn (1) major scientific and historical models, (2) about the nature of models and modelling, and (3) to produce and revise models (Gilbert & Boulter, 1998; Justi & Gilbert, 2002). The present findings support some hints for teaching about models and modelling in biology education which concern (1) and (2), i.e. the learning *of* models and the learning *about* models.

First, the findings suggest that students primarily view three-dimensional, concrete models as *real models*. Opposed to this, models in other modes of representation, e.g. model organisms or diagrams, were not seen as models in the same manner. Consequently, teachers may not only discuss concrete models but also model organisms or more abstract models in biology classes to illustrate the diversity of biological models. As there are common characteristics of scientific models (e.g. the relation to a target; Van Der Valk, Van Driel, & De Vos, 2007), it should be discussed why such diverse entities like material objects, diagrams, and organisms are called models. Above that, the present findings as well as other authors (e.g. Grosslight et al., 1991) propose that students understand the predictive nature of models only to a relatively small extent. However, since this is one major purpose of models in biology (cf. Krell et al., 2012) students should be aware of it as a part of the nature of models and modelling in science. Consequently, teachers may explicitly discuss not only the descriptive nature but also the predictive nature of models (Treagust et al., 2004). Finally, as the present study aimed at developing a student-based typology of biological models, one additional educational implication may be highlighted. As discussed in other areas of science education (e.g. Urhahne, Kremer, & Mayer, 2011), the nature of models may be easier to understand in some contexts than in others. This is also highlighted by Harrison and Treagust (2000) who emphasise that different model types put different cognitive demands on students. The present findings suggest that, e.g., the explanatory power of models is better understood in the context of abstract models (‘explanatory models’; Figure 1) than in the context of concrete models (‘iconic models’). Consequently, teachers may use ‘explanatory models’ to introduce this part of the nature of models. In the same sense, single models have a comparatively high mean score in the factor ‘prediction’ and therefore seem to be appropriate to introduce the predictive nature of models in biology classes, e.g. the theoretical reconstruction of *H. neanderthalensis* (*ms*=2.57). Hence, the proposed typology of biological models may guide the selection of models (i.e. of learning contexts) to introduce the multifaceted nature of models in biology classes.

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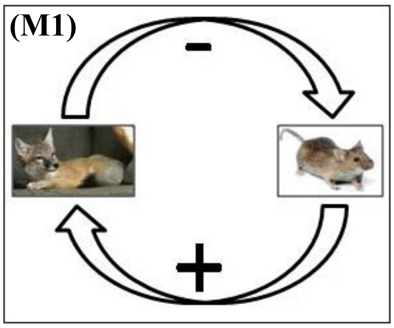
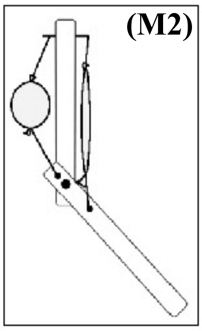
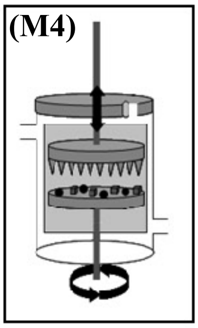
Appendix

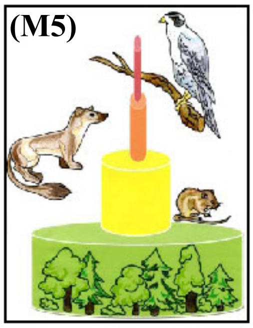
Pictures of the 16 models which have been used for characterising biological models. The models are numbered like in Table 3, i.e. arranged by their mean score in factor 1 (Table 2).

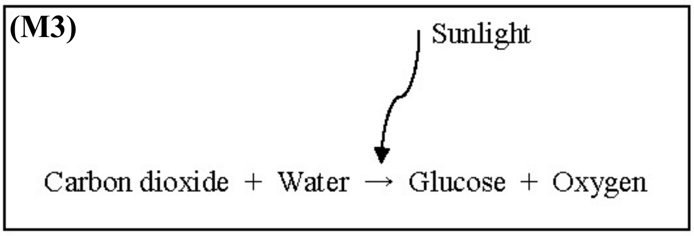


(M1)

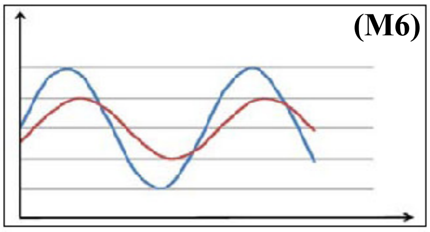

(M2)

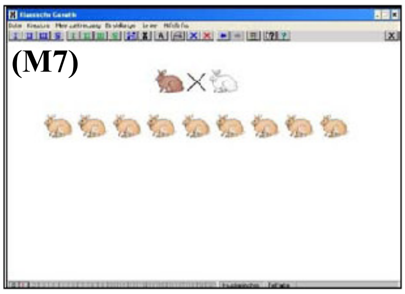

(M4)

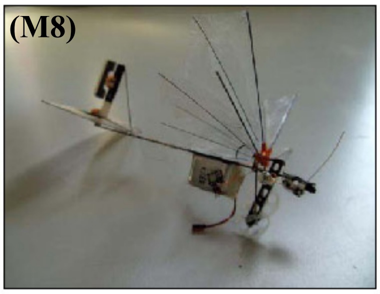

(M5)



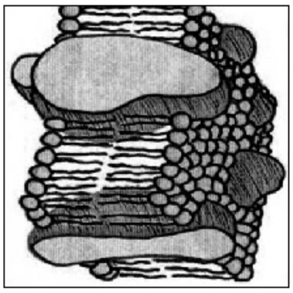
(M3)


(M6)

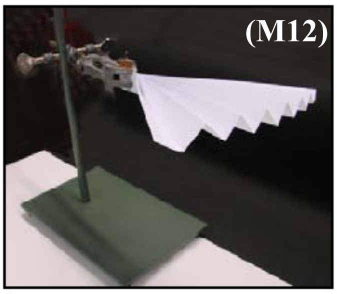

(M7)


(M8)

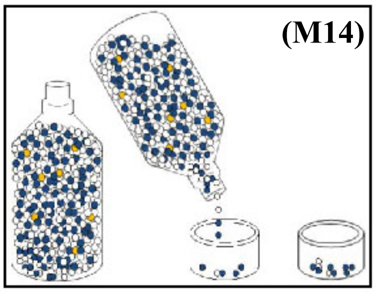

(M9)

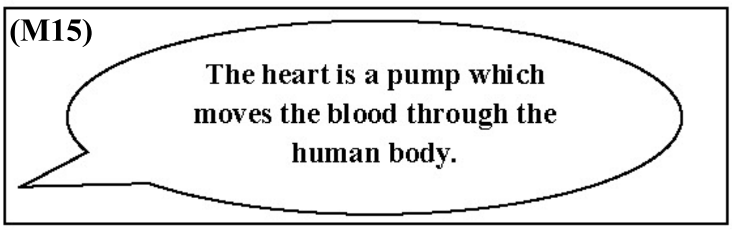

(M10)


(M11)

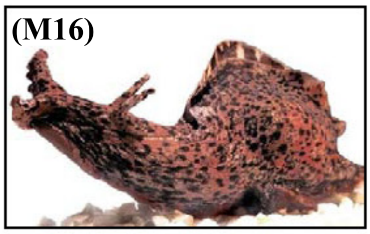

(M12)


(M13)


(M14)



(M15)


(M16)