A second order cybernetic model of scientific conceptual understanding: The case of kinematics

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ABSTRACT

Even if difficulties of the pupils in sciences are diversified, most seem linked to deficiencies in their understanding of basic concepts. Since about twenty years, different researches tried to bring solutions in this problem, favouring the multiplication of directives that can be applied to science education. To integrate their results, we offer a second order cybernetic model of scientific conceptual understanding which allows, not only to describe all the paths learners took to understand, but also to choose instructional strategies of education appropriate to do so.

Keywords: Learning model; Scientific understanding; Conceptual network; Cognitive schema; Instructional strategy

1. INTRODUCTION

At the dawn of the XXIst century, it has become essential for young people to undergo basic scientific training, either to favour their integration in a society more and more dominated by science and technology or as part of their studies in a scientific or technical domain. High schools, principally responsible for the acquisition of basic scientific learning and the training of new scientists, attains these purposes only partly as many young people leave school without completion of their high school diploma and others choose not to continue studying in a scientific or technical domain [1]. In this respect, difficulties students experience throughout their scientific studies seem to be connected to deficiencies in their understanding of basic concepts which remain, even after having completed several courses in a specific scientific domain [1,2]. In reference to these issues, a question arises: Is there a model of the process of understanding scientific concepts which would account of various difficulties in science learning experienced by high school students? To answer this question, our research of a theoretical nature analyses and synthetizes the results of researches on conceptual scientific understanding. To integrate the results of these researches, we propose a model constituted by the main dimensions of understanding and their reciprocal relations.

2. METHODOLOGY

The theoretical perspective of this research aims at clarify what is general in the various aspects of the conceptual scientific understanding, to highlight variables linked to this understanding and their reciprocal relations, and to formulate them in the form of laws or principles, by trying to abstract it from individual characteristics of learners and from contexts [3]. Moreover, to give a better account of the complex character of the phenomenon of conceptual scientific understanding, we adopted a systemic method where variables are interrelated in the form of a organised whole, represented in form of a modelling schema [4].

To elaborate the model of scientific conceptual understanding, our research method consisted of performing, in an iterative way, the analysis and the synthesis of literature in this domain [5]. We briefly introduce the main steps of this research method:

1) The identification of the corpus of texts to be analysed concerning conceptual scientific understanding

Fundamental topics and texts concerning conceptual scientific understanding were chosen according to this topic. We therefore questioned two educational databases. The first one contains texts which are written in both French and English (FRANCIS). The second database contains texts that are only written in English (ERIC). This first selection of texts was made using the descriptor COMPRÉHENSION or its English equivalents UNDERSTANDING and COMPREHENSION, and by limiting articles and monographs chosen in the education and scientific domain.

2) The segmentation of texts in analysis units

The constituted corpus of texts was later segmented in units of analysis. The unit of analysis is defined as a segment of information which relates to a category [5]. The length of the units of analysis does not coincide with the linguistic segmentation of the text (sentence or paragraph) but rather tries to capture a main idea concerning the understanding of scientific concepts [6].

3) The location and coding of analysis units

Every unit of analysis is described with the aid of one or of several keywords which characterises the information contained in unit. Using keywords allows one to condense content, and makes it easier to find and compare the research results of the different authors with
respect to a topic or a sub-topic of scientific conceptual understanding. To this end, keywords have to be expressed in a way that is general enough to allow comparison (and synthesis) and specific enough to facilitate their location and the treatment of information during the analysis [5].

4) The structuring of results obtained in a modelling schema of the scientific conceptual understanding

Once the thesaurus for scientific conceptual understanding had been constituted, we calculated the frequencies of the keywords appearance and the associations between keywords in the units of analysis [6]. The analysis of these frequencies allowed us to identify the important keywords and to connect them in the form of a schema [7].

5) Validation of the model of scientific conceptual understanding

The modelling schema is later subjected to a technique of validation based on the clarification of paradoxes identified in the studied texts. Indeed, the highlighting of a paradox allows the modification of the conceptual structure of a theoretical schema and the clarification of this paradox allows the refinement of this schema by specifying the limits of the studied concepts [8].

Finally, in spite of the linear character of the steps of the research method described above, the analysis and the synthesis of the content contains feedback loops at every step which allow the process to converge on a “prototype” of the model of scientific conceptual understanding [5]. Given the theoretical character of our research, we did not undertake an empirical validation of this model so that this validation will have to be completed in subsequent research.

3. RESULTS

Presentation of the model of scientific conceptual understanding

Steps of the model

We specify now the different steps of the model of scientific conceptual understanding and its structure. This model can be conceived as a cognitive system which interacts with its environment by collecting information and producing answers. During the elaboration of one’s understanding, the learner’s conceptual structure, semantic in nature and constituted by schemas, acts as a cognitive tool which, not only chooses and stores information from its environment, but also transforms it to produce better adapted schemas. As a result, schemas mobilised by the learner when he interacts with the phenomenon are changed during treatment process to gain a more adequate understanding of the phenomenon [4]. As a learning approach, understanding becomes divided into three parts: the conditions of understanding, process of understanding and product of understanding (see fig 1).

Conditions describe the requirements at the entry of the system, which contains two components: the initial state of understanding of the learner and the scientific concepts to be understood. Process describes the way the interaction between the learner and the scientific concepts takes place.

The product specifies the characteristics of the final state of understanding [9].

![Fig. 1 Schema of the model of scientific conceptual understanding](image)

Main sense of information transfer

The main sense of the information transfer of information is directed from conditions to the product by way of the process [9]. This transfer can be influenced by the choices or decisions of the learner (see fig 1). Indeed, from conditions to process, learner’s schemas adapted to the study of the scientific concept are chosen among all of the available schemas according to the characteristics of the concept. From process to product, the learner chooses to continue or to close the activity of understanding if he judges that his state of understanding is satisfactory [10]. The information transfer form conditions to process and form process to product can also be influenced by emotional or social factors. For example, it seems that beginners prefer schemas having a high degree of correspondence with the structure of the studied concept. This preference limits the level at which the beginners can treat information later [11].

Feedback loops

We have described up to now the information transfer from conditions to process and finally to product. However, the information transfer can also take place in the reverse sense. This inverse transfer is called feedback and allows one to reinvest the results of every step at a previous step, constituting feedback loops [12, 13]. The first feedback loop, going from conditions to process and conversely from process to conditions, means that the learner turns his attention to the object of study (concept, phenomenon, law, principle), that some of his cognitive schemas are activated to treat the information coming from this object, and that meanwhile some understanding difficulties appear (see fig 1).

The second feedback loop, going from process to the product and reciprocally from product to the process, means that the new organisation of knowledge changes the understanding process (see fig 1). For example, new links established between some elements of the representation of the learner can lead him to search additional information, to incorporate some contributions of his peers toward the development of a more general schema, etc.

The third feedback loop consists of the use of the products of this approach as new ‘entry’ in the system, which launches a new understanding cycle (see fig 1). This cycle allows one to open the way to new learning: generalization of the new concepts, their use in the resolution
of problems, and their application in daily life [12,14]. The repeated use of the understanding cycle allows learner to provisionally occupy a series of states of understanding of increasing complexity [15]. These states distinguish themselves by their degree of organization of knowledge and the new operations which this organization allows. The series of states of understanding defines all of the levels of understanding of increasing complexity [4].

External influence on the approach of understanding
Moreover, the approach of understanding is opened to external influence of emotional or social nature. Knowledge which the pupil uses often comes from interactions with daily objects. As such, learner’s conception of science, the value he grants in scientific activities and the competence he recognizes in the accomplishment of these activities were influenced by an extended contact with the school environment [16].

Viewing the whole approach of understanding
By viewing the whole approach of understanding in sciences, we first notice that it is initiated when the cognitive schemas of the learner are mobilised for representing the object and its properties [16]. This representation includes two distinct processes: the identification of various aspects of the object (differentiation) and the synthesis of these aspects in a consistent conceptual structure to fulfil different scientific functions (integration) [5]. The higher or lower ability of the learner to differentiate and to include the various aspects of the object (that it is a phenomenon, a concept or a scientific law) results into the acquisition of more or less efficient cognitive schemas to predict and to explain this phenomenon [15]. These cognitive schemas constitute new entries during the launch of a new understanding cycle. Therefore these new schemas can contribute to the study of various situations that are similar or different from the initial situation, favouring generalization and knowledge transfer. Understanding is therefore iterative, continuing until learner is satisfied [10].

Regulation of the approach of understanding
Finally, the presence of explicit regulation mechanisms in the schema of the approach of understanding results in several important consequences for learning: 1) they partly explain the gap between qualitatively different conceptual structures, 2) they lead to the organization of a hierarchy of acquired knowledge. Indeed, the reinvestment of the products of understanding as new entries does not only increase the knowledge of the learner, it transforms the way information is treated since schemas are the conceptual tools with which the learner interprets and organises his environment [4,14]. Moreover, this reinvestment facilitates self-regulation, i.e. when the learner regulates his or her learning. More precisely, learners having good self-regulation skills generate feedback for themselves providing information about what learning objectives have been mastered and what it is necessary for them to do in order to pursue new objectives, while in comparison, learners not having such skills rely on external feedback, given by the teacher or the school textbook [16].

4. PEDAGOGICAL APPLICATIONS: THE CASE OF KINEMATICS

Description of the pupil’s evolution of understanding
If the schema of approach aims at describing factors which influence understanding and their organisation, at least in its main lines, the choice of instructional strategies to favour understanding depends on the particular characteristics of pedagogical situation [5]. As a result, to go from the description of the way understanding evolves to the choice of activities allowing to favour this understanding, one first needs to specify the evolution of the understanding of learning and secondly to specify requirements relating to each step of the approach of understanding by taking into account characteristics of the pedagogical situations found in sciences. We aim in this section to satisfy the first requirement and in the next section to satisfy the second.

In this respect, to describe the evolution of the understanding of learning, our approach consists in simulating what would be an approach of ideal understanding when it is carried out according to steps and by respecting relations between its elements [18]. In that way, by applying this approach repeatedly, it is possible to explain the various progressions of the learner’s understanding. Indeed, if conditions and products of understanding define the points of departure and of the arrival of approach, the process of understanding allows to link these two states. And yet, the process of understanding in sciences is constituted of two operations: the identification of pertinent factors of a concept and the formulation of a rule which allows to link those factors to produce a new concept [17].

These operations act on two types of variables: on one hand, all the concepts of domain, say kinematics, and on the other hand, all of the learners’ representations. Moreover, this approach is applied whatever is the learner’s actual level of understanding and is therefore independent of the specific understanding cycle (see section 3). As a result, this approach ramifies by iteration into various paths according to the state of understanding (partial or complete) of different concepts of the aimed domain. The set of all these paths constitutes what we call a network of understanding [19]. An example of such network is given in the face 2 with respect to the speed concept [17].
Instructional strategies fostering scientific conceptual understanding
To formulate instructional directives, it is necessary for us to first specify the frame in which these are going to be inserted. Our approach, centered on significant learning, aims at studying the development of the understanding of the pupil in the educational contexts which it influences [17]. In regards to the approach of understanding, we aim to show the complementarity of instructional strategies intended to guide the pupil in their approach of understanding by respecting the systematic character of this approach [20, 21]. It is from this perspective that we suggest the following instructional strategies of education for each of the steps of the approach of understanding: 1) establish the conditions of understanding; 2) favour the process of understanding; 3) favour the evaluation of understanding by the pupil; 4) favour the self-regulation of the approach of understanding.

Establish the conditions of understanding
Above all, conditions allowing interaction between the cognitive schemas of the pupil and aimed scientific concepts must be set up. On one hand, this interaction required that the activities (either to explain a scientific phenomenon or to resolve a problem) allow pupils to mobilise their current cognitive schemas and, on the other hand, that these schemas, once activated, could be made public and explicit in order to be studied, either by the pupil (metacognition), or by the teacher (diagnosis of previous knowledge).

Favour the process of understanding
To fill up the gap between the aimed concepts and the previous knowledge of the pupil, two approaches have been offered [14,22,23]:
- Assuming the naïve schemas of the pupil and scientific concepts are irreconcilable, the first approach plans to replace these naïve schemas with scientific concepts by fulfilling some conditions.
- Assuming the naïve schemas of the pupil and scientific concepts share common points, the second approach aims at the gradual modification of the naïve schemas first into scientific concepts by giving the pupil support and adapted guidance.

These two approaches led to the development of distinct instructional strategies. In the first approach, the replacement of the pupil’s cognitive schemas by scientific concepts is made by stressing the conflict between the two and by persuading the pupil of the necessity to replace the first with the second. To this end, it is necessary to lead the pupils to express their schemas in relation to the aimed concept (represented by a scientific phenomenon), then to lead the pupils to become aware of the insufficiencies of their schemas to explain properties of the selected phenomena. It is then a matter of introducing the scientific concept as a credible, comprehensible and fruitful alternative [10,23].

The second approach consists in favouring the progress of the pupil towards a better understanding of scientific concepts from what he understood already, by offering structured activities which guide the pupil’s approach [22]. In this respect, we listed two types of intervention. The first type aims at leading the pupil to progressively model a group of phenomena associated the same concept or principle, allowing the pupil to identify important factors and to formulate the rules which explain the observed properties [24,25]. The second type encourages the pupil to compare its schemas directly with the scientific schemas, for example by offering analogies or conceptual models allowing the pupil to choose pertinent information, to organise it and to connect it with its previous knowledge [26,27].

Favour the evaluation of understanding by the pupil
To make sure that the product of understanding, that it is a concept or a model, answers scientific criteria, the pupil can review the concept or model in a retrospective way. This is done by critically examining the approach undertaken to acquire this concept or this model or in a prospective way by proving that the concept or model allows the fulfillment of various scientific functions (prediction, explanation, etc.) [28,29]. In the first case, evaluation allows to reconsider the characteristics of the approach of resolution of scientific problem to show possible variations and to foresee directions of investigation allowing to generalize the schema or the acquired model. In this respect, it is important to teach the pupil not only how to work out models of a given domain, but also to teach the way of reviewing them while leading him to reflect on their nature and their role [25].

In the second case, it is a question of first determining if the constructed schemas can be applied to similar situations or favour the acquisition of new knowledge as well as to specify the limits of the solutions found and their application field [30].

Favour the self-regulation of the approach of understanding
When the instructional approach is constituted of very structured activities, it limits the opportunities offered to the pupils to choose, and its implementation is then regulated by the teacher who must make sure that its various interventions are in agreement with the present state of understanding of the pupil. Yet, considering the diversity of experiments and knowledge of the pupils, it is unlikely that such an instructional approach is suitable for all pupils and as a result allows an optimum regulation of their approach of understanding [31].

That is why an approach favouring the self-regulation of the approach of understanding by the pupils should include instructional strategies that encourage them to take control of their own learning. To this end, this approach should include various dispositions to encourage the pupils to mobilize and combine their cognitive strategies (such as metacognition and motivation) in order to identify their knowledge and skills, to plan their approach and to reflect on the results obtained in order to possibly change their cognitive strategies and give them a higher efficiency [16]. In this respect, the following strategies proved to be efficient to develop the metacognition and the self-regulation of the pupils:

1) Strategies combining the modelling of phenomena, the evaluation of models produced by the pupils according to some criteria and debate between pupils on the role and the utility of models [25];
2) The environments which, while giving challenges adapted at the level of the pupils, guide them in their approach by giving them different supports
such as various information sources, feedbacks and simulation [32].

5. DISCUSSION
In this article, we argued for a systemic approach to study scientific conceptual understanding. Hence, the model of understanding proposed here can be defined as a cognitive system composed of elements in interaction. One of main characteristics of this model consists of its regulation mechanisms that guide the learner toward his goals, which makes it a cybernetic mechanism [33]. This regulation can be made in an external way, for example by the teacher, or in an internal way, by the learner himself, who then takes charge of his own learning processes, i.e., reflecting on his actions, assessing them and planning according with he has learnt, while using his auto-regulated skills.

In such a case, the model of scientific conceptual understanding can be classified as a second order cybernetic mechanism [34]. Its essential characteristics are similarity between cycles of understanding and auto-reference throughout each cycle. Indeed, by going through the different paths of the understanding network, (see fig. 2 for the speed), we can observe that relations between neighbouring concepts are governed by two processes (identification of factors and integration of these factors into a new entity) which repeated themselves from the left (most basic concepts) to the right of the network (acquisition of the speed concept).

The self-reference generates the paradoxes that have been mentioned earlier (see section 2). For example, one such paradox is the learning of autonomy in an educational situation. Indeed, one can wonder how it is possible to teach a pupil how to take care of his own understanding. Let say for example that we succeed in this teaching, and as a result the pupil has acquired a greater autonomy. Obviously, a direct teaching approach would not be the appropriate teaching strategy, since one can hardly imagine a student acquiring autonomy simply by being told, and explained, how to be autonomous. But even in the case of more active situations where the pupil, for example, learns to model the properties of chosen phenomena, can we say that he has acquired autonomy?

Research has shown that it is not the case. As such, using or developing models to predict and explain scientific phenomena may not be enough for students to use these skills in other contexts. In fact, it may impede the construction of the models itself. Schwarz and White [25] have shown that it may be necessary, in addition to activities of modelling and inquiry, to include knowledge about the use of models as well, i.e. meta-modeling knowledge. Referring to the model of scientific understanding described here, their activities would include the second feed-back loop, developing models of scientific phenomena and reflecting and evaluating their nature, purpose, and utility in predicting and explaining properties of these phenomena.

6. CONCLUSION
Difficulties experienced by pupils during scientific learning find their origin partially in misunderstandings which manifest themselves in a manifold way in different domains while sharing some similarities. To explain these difficulties and to plan efficient interventions intended to favour pupils' understanding, it is important to explain the way scientific conceptual understanding takes place. In this respect, our model of scientific conceptual understanding accomplishes this objective with two conceptual tools: 1) a network of understanding, which allows for the description of different paths of learning when a pupil advances in understanding; 2) a schema of the approach of understanding, which describes the organisation of different stages of understanding so that it is possible to choose strategies of education most adequate to each of the stages of approach.

In regards to the limits of our research, the method of contents analysis using keywords tends to rigidify the collection and analysis of data. Indeed, the keywords that appear from the analysis do not allow one to give an account of the nuances brought by the authors. In addition, by classifying units of analysis with the aid of keywords, the coding method does not take into account the evolution of terms used in the field of the understanding of concepts in sciences [35]. Moreover, the accent put in this research on the identification of variables and their interrelations cannot give an account of the wealth of other perspectives, some for example more centered on specific characters of context or of individuals [36].

Despite these limits, the integration of the results of research on understanding in a scientific conceptual model can enrich pedagogic practices linked to understanding and to point out new research avenues. Above all, the approach suggested here to favour understanding allows the teacher to choose according to the learner’s actual state of understanding the instructional strategies most adapted to guide its progress.

Finally, it is important to include the emotional and social aspects in the model which would aim at the entire development of the pupil. More precisely, the influence of emotional and social factors in the development of understanding should be explained more. For example, we can assume that dispositions provoking interest would allow to engage pupils in the understanding process. Inversely, factors of emotional nature as a weak tolerance for ambiguity (for example when a pupil in transition between two levels of understanding is confronted with contradictions between his schemas and new knowledge) can unsettle the development of his understanding [37]. It is also important to identify factors allowing for the support of motivation throughout the approach of understanding if we want as educators to withdraw all of benefits of our interventions [38].

7. REFERENCES
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