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Identifying Changes in a Student's Mental Models and Stimulating Intrinsic Motivation for Learning During a Dialogue Regulated by the *Teachback* Technique: a Case Study

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Abstract

The aim of this paper is to show how an innovative technique can be used to introduce a method for uncovering intrinsic mechanisms that motivate changes in students' mental models. The theoretical framework used to develop the method is based on the ONEPSY (ONtology, EPistemology and PSYchology) model. The ONEPSY model is rooted in the theoretical constructs of cognitive psychology (Johnson-Laird) and artificial intelligence on mechanistic mental models (de Kleer and Brown) as well as the psychological theories developed by Piaget and others about the construction of knowledge and cognitive mechanisms that enable us to learn and survive in the world. This method was used when regulating a dialogue between a teacher (interviewer) and a student (interviewee) and also when analysing this dialogue subsequently. Pask's *teachback* technique was used to regulate the interview and showed its effectiveness for helping a student both to identify his difficulties and to be able to overcome them; it also helped him to develop the ability to build models that gradually move closer to scientific models based on intuitive reasoning (mental models). The emotions experienced by students during this process have been shown to be a decisive driving force—intrinsic motivation—for constructing and reconstructing their intuitive models and acquiring increasingly satisfactory mental models. The different regulatory processes controlled by the interviewer during the dialogue have also been outlined.

Keywords ONEPSY model · *Teachback* · Dialogue regulation · Emotion · Mental model · Intrinsic motivation

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Introduction and Objectives

It is clear from literature on education that dialogue based on the triadic pattern (question–answer–evaluation) between teachers and students has limitations, even though it is still widely used in educational practice (Kaya et al. 2014, 2016; Lemke 1990; Margutti and Drew 2014). It has a negative impact on students' relationship with scientific knowledge (Ford and Wargo 2012) and promotes the *stigma of error* (McNeil and Pimentel 2010), discouraging students from participating in debate. However, when the triadic pattern is abandoned, students have been shown to adopt a more active attitude (de Witt and Hohenstein 2010) making dialogic interaction possible (Kawalkar and Vijapurkar 2013).

Although various alternatives to the triadic pattern have been proposed, the authors have a special interest in those that opt for dialogue in class for several reasons, on the basis of our own experience and on information from the literature: (a) if students are given the chance to practice dialogue in class, it comes naturally to them; (b) this allows a classroom atmosphere based on respect and an unconditionally positive relationship among participants to be created, enabling each of them to express their ideas openly without feeling threatened (Bellocchi et al. 2014); (c) this facilitates students' construction of knowledge and enables them to gain and grow in confidence in their ability to do so (Bolton 2005); and (d) this all helps them to improve their critical thinking (Frijters et al. 2008).

However, despite these advantages, in practice, school dialogue encounters a potentially decisive drawback: the inability to make reasonably accurate predictions about what direction dialogue will take (Scott et al. 2006). This also introduces an uncertainty factor for teachers that is often perceived as involving an unacceptable level of risk.

Objectives

To try to alleviate this problem, the authors have developed a technique to regulate and analyse school dialogue, with a highly specific theoretical basis. This technique enables teachers to help students to perceive the problems encountered during their science learning and solve them by themselves.

This article therefore aims:

(1) To develop a method of analysing and conducting *didactic dialogues* to enable students to make scientifically valid inferences based on a well-grounded theoretical framework.
(2) To reveal the processes produced during dialogue, regulated by the *teachback* technique: the interviewer's analyses of the pupil's mental models and emotional states and his decisions about how to conduct the interview.
(3) To check the usefulness of *teachback* regulation to enable students to overcome their learning difficulties and to learn to reason in a scientifically acceptable manner.

"Method for conducting and analysing teachback dialogues", "Processes in a teachback dialogue" and "Usefulness of the teachback dialogue" sections correspond to one of these three objectives.

The paper also presents the results of a more extensive study (Aliberas 2012), but only a small selection of the data and analyses involved in the study has been included, enough for readers to grasp the process and analysis of didactic dialogues.

Theoretical Framework

For the purposes of the study, we tried to make the most of the students' natural reasoning mechanisms and the different processes by which people come to agree on certain knowledge. The research therefore used the *ONEPSY* model for the processes of constructing and reconstructing common sense knowledge and the *teachback* technique, which encourages interpersonal communication for the purpose of reaching an explicit consensus based on Pask's Conversational Theory.

The ONEPSY Model

The ONEPSY model was put forward by Gutierrez and Ogborn (1997) and Gutierrez (2001) and is based primarily on the *mental model* concept described by Johnson-Laird (1983), the work carried out by de Kleer and Brown (1981, 1983, 1984) in the field of artificial intelligence and other authors such as Piaget (1975), Sorensen (1992) and Reiner and Gilbert (2000).

The model aims to describe in detail the processes by which humans that are attempting to understand reality and act on it effectively build mental models of the physical systems that they consider important at any given time, reconstruct them until they are satisfactory and then use them to infer future behaviour. These are implicit cognitive mechanisms which enable us to adapt to our environment and the changes that this may undergo and are essential for keeping abreast of our contact with the world (*survival necessity:* Sorensen 1992; Reiner and Gilbert 2000; "brute survival necessity": Nola 2004 p 374).

The ONEPSY model follows Johnson-Laird, de Kleer and Brown's insights and establishes that during these mental processes (Fig. 1), individuals start by making *a first representation* of the physical system whose operation they are trying to understand, abstracting the *entities* and their *properties* that seem relevant and necessary to explain the system's behaviour, depending on their interests at the time, and thus establishing a particular *ontology.* This first representation is of course bound by sociocultural contexts and by the subjects' existing knowledge about the world, although the influence of these elements is not necessarily at conscious level.

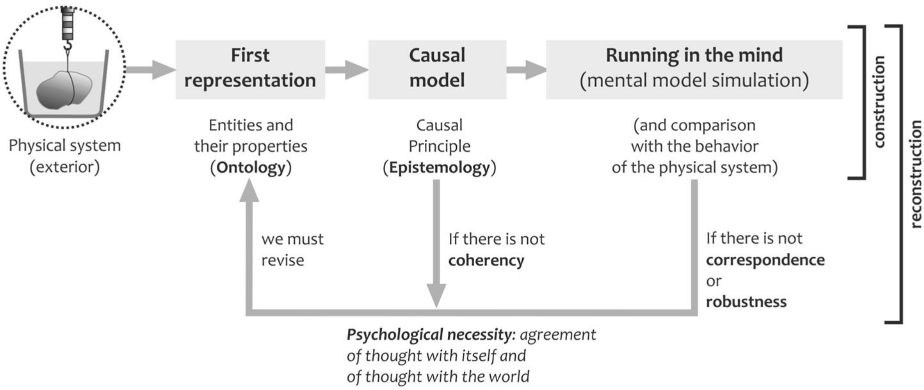


Fig. 1 Operation of the process of constructing and reconstructing mental models according to the ONEPSY model (adapted from Gutierrez and Ogborn 1997 and Gutierrez 2001). As can be seen, the model incorporates ONtological, EPistemological and PSYchological conditions, hence its name

A *second representation* is then derived from the first, and in the case of dynamic physical systems, the second representation is a *causal model*, which *is constrained* by the causal principle (Bunge 1959) in such a way that all relationships between the entities and their properties are causally governed. The causal principle is the inferential rule that enables individuals to develop an *explanation* of the behaviour of the physical system and make *predictions* about its future behaviour; it functions as a "true criterion" for validation of the knowledge of the world that is produced, playing the role of a *spontaneous epistemology.* Obviously, this knowledge is valid according to the way in which the subject believes that the world functions. It is subjectively "true" or "valid". For the subject, it is enough for *coherency* to exist between the causal principle and the ontology he or she has already constructed.

The causal model can be mentally "run", executing a mental simulation (in the computational sense) that puts the causal model in motion, enabling the system to behave in a specific way by means of a sequence of events, each one causally related to the one before. This *execution* enables comparisons to be drawn between the working of the mental model and the behaviour of the external physical system; it is therefore possible to evaluate the *correspondence* between the mental model and the physical system. The model must also retain its correspondence when the behaviour of the system, or similar systems, differs to some extent from its real behaviour. This constraint is call *robustness.*

If the model thus constructed lacks coherency, correspondence or robustness, subjects become aware of *the shortcomings in their existing model* and *are dissatisfied*. They feel that the model *must be reconstructed.*

Johnson-Laird and de Kleer and Brown's account of the mechanisms for constructing mental models of dynamical physical systems so far.[1]

In addition to the above, and in accordance with contributions from neuroscience, we believe that evaluations of mental models also have an important emotional (physiological reaction) and sentimental (subjective experience) component, so that we perceive them as positive or negative. Damasio (2018) emphasises that feelings are omnipresent in our mental life:

> Feelings always accompany the unfolding of life in our bodies; that is, everything that one perceives, learns, remembers, imagines, reasons, judges, decides, plans or mentally believes. (p 144 Spanish ed., authors' translation)

According to Damasio, feelings can basically acquire one of two mutually opposing values:

> Feelings necessarily have a *valence*; that is, they are good or bad, positive or negative, desirable or undesirable, pleasant or painful, agreeable or disagreeable. (p 221 Spanish ed., author's emphasis)

They are also fundamental for stimulating learning, for example:

> The majority of emotions and feelings are essential for boosting the intellectual and creative process. (p 146 Spanish ed.)

[1] de Kleer and Brown call these models *mechanistic mental models*, since a world ruled by the Causal Principle is mechanistic. However, both authors (Johnson-Laird and de Kleer and Brown) give an account of the spontaneous construction of mental models of dynamic physical systems using the Causal Principle as the inferential rule for formulating explanations and predictions.

In short, we must expect individuals' actions and decisions—and consequently the emotions and feelings that these generate—to be strongly conditioned by their satisfaction or dissatisfaction with the mental models they have constructed.

But one question remains: why do people spontaneously feel the need for their models to be coherent, correspondent and robust? Psychology could help to provide an answer.

When Piaget (1975) explains the equilibration mechanism that is responsible for developing of mental structures, he points out two interesting processes: assimilation, by which people transform incoming information so that it fits in with their existing thinking, and accommodation, by which people adapt their thinking to incoming information. Piaget states that these two adaptive cognitive mechanisms *satisfy the psychological need for thought to be in agreement with itself and with the world*.

Piaget's concept was introduced into dynamic physical system model, thus *closing the cycle* of the construction and reconstruction of mental models: *The mechanism that drives the reconstruction of mental models is the psychological need for thought to be in agreement with itself and with the world.*

Some Comments on the ONEPSY and Conceptual Change Models

Conceptual change has been the main line of research in Science Education since Driver and Easley (1978) wrote their seminal paper "Pupils and paradigms: A review of literature related to concept development in adolescent science students". The paper marks Piaget's decline as a reference in this area of research and the rise of Ausubel's paradigm. Ausubel's (1968) "Educational Psychology: A Cognitive View" underlines the importance of pre-conceptions (intuitive ideas that people have before being taught) in learning. Driver and Easley called these intuitive ideas "alternative frameworks" or "misconceptions", and it was these terms which spread first in the new line of research. Researchers soon reported on the difficulty involved in eradicating these intuitive ideas, and a great deal of effort was made to formulate "conceptual change models" that tried to make sense of the data and offered ways of overcoming the difficulties (the first attempt was the Posner et al. (1982) model known as the PSHG model). The abundance of literature produced in the search for models and methods to explain and overcome conceptual change is impossible to describe here, but for our purposes, it is enough to mention the state of the issue as presented in reviews from the field; the special issue of *Learning and Instruction*, Vol 4, Number 1 (1994) is devoted to conceptual change, for instance. In the Introduction to the issue, Vosniadou (1994) writes:

> The question of how conceptual change is achieved and the specification of the mechanisms that bring it about is one of the fundamental problems of cognitive psychology today (p 3).

At the end he comments:

> Before closing I would like to draw attention to an important question often not addressed in discussions of conceptual change. This is the question regarding the driving force behind conceptual change. Is there something that drives conceptual change? How do we explain conceptual change? (p 5).

Caravita and Hallden (1994: 98) and Spada (1994: 115) highlight the same problems.

Five years later, another review appeared that brought the state of research into conceptual change up to date*: New Perspectives on Conceptual Change* (Schnotz et al. 1999). One author commented:

> As we look at the future of conceptual change research, it becomes apparent that what is needed is […] a theory of learning that specifies the mechanisms that can take an individual from one level of cognitive performance to the next … Further research on how to promote conceptual change should certainly take the turn of understanding and describe these processes in greater detail (Vosniadou 1999, pp 9-10).

Duit (1999) also draws attention to the need to "investigate both the fine structure of conceptual change processes and the impact of supporting conditions of conceptual change" (p 282).

Some 20 years later, the discussion about how conceptual change comes about continues and still focuses on the mechanisms that could explain the processes involved. An example is the review that diSessa included in his paper "Conceptual Change in a Microcosm: Comparative Analysis of a Learning Event" di Sessa (2017). diSessa asks himself:

> "Why this article, now?
> "Understanding the basic issues of the nature of elements of mind (subconceptual elements, concepts, theories, ontologies...) that contribute to or block conceptual change, together with their relational structure (e.g., relative coherence) and dynamics during learning (learning mechanisms), *remains a compelling challenge for the field to resolve*" (p. 4) (authors' emphasis) .

diSessa begins with an extensive update of the literature, summarising all the tendencies in the field in two approaches: those of Vosniadou, which he called "theory–theory" (T–T), and Chi, which he called the "ontological view" (OV). He then describes his approach and discusses the results, comparing with Vosniadou and Chi's mechanisms and ruling them out.

The learning mechanisms that diSessa describes are based in his p-prims construct (diSessa 1983). Sometimes, these p-prims are activated when the subject observes phenomena that "just happen naturally" (as equilibration p-prim), and thus, the subject does not look for agents [causes] that explain the behaviour of the observed phenomena [systems]. However, there is normally an agentive p-prims that explains the phenomenon's behaviour (such as Ohm's p-prim). To explain a phenomenon successfully, p-prims frequently combine into compound structures (Causal Scheme, diSessa 2014) in which they form a causal chain.

diSessa uses clinical interviews as a method for recognising at fine-grain level the processes of activating p-prims, how the mechanisms act, the processes they follow and the learning outcomes produced. In his opinion, this method is quite different from those used by Vosniadou and Chi: "I believe that it is fair to say that neither the TT nor the OV have put forward empirical analyses at a small grain-size" (p. 8).

The ONEPSY model was first developed within the conceptual change framework (Gutierrez and Ogborn 1997), and its main aim was to describe "the fine structure of conceptual change" (Gutierrez 2001). In the authors' opinion, the ONEPSY model describes this more richly and in more specific detail and also gives an account of how the cycle of construction and reconstruction of knowledge is closed. Causal chains as spontaneous reasoning mechanisms are widely reported in science education literature (see, for instance, Gutierrez 1994; Russ et al. 2008; Viennot 1996, and Kuhn 2012). Causality can explain many phenomena, but we feel that the constraints imposed by ontology and other psychological factors enrich and make the mechanisms that drive the changes more explicit. The research described in this paper uses a type of "clinical interview" adapted from Pask's *Conversational Theory* and named the "teachback technique". Genuine clinical interviews can sometimes be compared with Socratic dialogue; while empirical evidence shows that this is effective (Boa et al. 2018; Maxwell and Melete 2014), it is not known why. *Teachback* can explain its effectiveness on a theoretical basis (Pask 1975, 1976); in addition, *teachback* interviews alter the roles of the participants in the dialogue: in this case, the novice plays the role of the expert and, inversely, the expert acts as novice (see below).

In some of our works, we give an extensive account of Pask's theory (Gutierrez 1994, 2003). In what follows, the *teachback* technique as applied to conduct didactic dialogues is demonstrated.

The *Teachback* Technique

Pask proposed the *teachback* technique to facilitate the process of gaining access to the content of experts' intuitive non-conscious knowledge (1975). The technique consists of the following steps: (a) the interviewer asks the expert for an explanation ("teach me") of what he/she knows about the topic of interest; (b) the expert provides this; (c) the interviewer then tells the expert ("teachback") his/her understanding of what the subject has just explained; and (d) if the subject recognises what he/she meant to say in the explanation to the interviewer, the interview can move forward; if not, the expert and interviewer resume *teachback* exchanges until the expert agrees with interviewer's understanding of what he/she thinks. The most interesting part of this exchange process is that interviewers are limited to "giving back" what they themselves have explained about the issue to the expert, without adding any new information. The expert therefore feels pushed to rephrase or complete his/her replies to try to make the interviewer understand, until he/she is persuaded that the interviewer has effectively understood (consensus).

Gutierrez (1994) adapted the *teachback* technique for educational purposes, assigning the role of the expert to the student, with the teacher playing the role of the interviewer. In this way, teachers can gain access to students' implicit thinking.

Now that a theoretical framework has been provided, the three objectives proposed for this paper can be addressed in the three sections that follows.

Method for Conducting and Analysing *Teachback* Dialogues

The theoretical framework presented above provides several tools for conducting dialogues regulated using the *teachback* technique as well as their subsequent analysis.

As mentioned previously, when holding a *teachback* dialogue about a particular physical system, the teacher takes the role of *interviewer* and the role of *expert* (in his/her own worldviews) is allocated to the student; the interviewer therefore tries to ascertain the mental models that the student uses to understand the system. The interviewer's questions aim to clarify perceived ambiguities in the student's mental model which prevent him/her from reproducing it and running it correctly in his/her own mind.

The aim is that, by focusing the *teachback* process on ambiguities in what the student has said, he or she can try to resolve them without the interviewer providing him with any new information. If this succeeds, a *satisfactory* mental model can be seen in their responses (not necessarily identical to the "scientific" model); if it does not, the student is able to perceive that *coherency*, *correspondence* or *robustness* has failed. To solve the problem, he/she needs to reconstruct his/her mental model until it is finally *satisfactory*. The interviewer must be able to detect this entire process on the basis of the student's answers.

By examining the transcript of a didactic interviewer–student dialogue regulated by *teachback*, it is possible to highlight the processes that the interviewer uses to conduct the interview and to analyse the dynamics that push the student to make changes to his mental models (i.e. to learn). Tables 1, 2 and 3 were devised to highlight the processes taking place and included the following columns:

- *Turn*. Consecutively numbered interviewer and student turns, marked I and S.
- *Dialogue*. Verbatim transcript of the turns. Actions or significant events are described in brackets.
- *Analysis of the response, detection of ambiguities and generation of the reply*. When analysing the student's response, we attempt to describe the characteristics, whether satisfactory or not, of the *mental model* that he seems to be using; this analysis is marked (M). Perceived *ambiguities* are marked (A). The reply is provided on the basis of ambiguities detected, among other factors. Other regulatory processes carried out by the interviewer are as follows: evaluating and making strategic decisions about how to *conduct* the dialogue (C), contributing to communication by using *language* strategies (L), assisting in managing experiments on the *physical* system (P) and exploring the *social* consequences of the dialogue (S).
- *Emotional result and student reasoning*. Evaluations of *coherency* (COH), *correspondence* (COR) and *robustness* (ROB), along with their *satisfactory* (+) or *unsatisfactory* (−) nature, are shown where possible. These are the evaluations *that the student seems to make*, not those that the interviewer may make taking into account his or her own scientific ideas. The relationships between the properties that synthesise the final inference drawn by the mental model are then indicated, and where properties of the entities affect others, the relationship is indicated by an arrow (➡).

With all this, the method of conducting and analysing the dialogue is fully shaped.

Processes in a *Teachback* Dialogue

The method described above was applied to an 18-min dialogue on elementary hydrostatics, with the possibility of carrying out experiments, between an interviewer and a 15-year-old physics and chemistry student in the fourth year of secondary school (ESO). His teacher considered him as a middle level student. The dialogue consisted of 155 turns per interlocutor, three extracts of which are fully analysed here. The student had recently studied hydrostatics in class and had therefore been introduced to relevant concepts and vocabulary. The results of the analysis have been checked by two independent judges who were familiar with the method. They were provided with Table 1, which contains the necessary codes. The level of agreement was 92%, and full agreement was reached by consensus.

Extract 1: Turns 1-I to 15-S

The dialogue focuses on the change in shape of a ball submerged in water (Fig. 2) and the apparent decrease in the weight of a submerged object (Fig. 3).

1-I: In this case [Fig. 2: ball submerged], this ball is attached to the bottom. What did you think? That it would end up like A, B or C?

2-S: Like B.

2-I: Like B. Why?

3-S: Because [...] force or pressure is exerted downward. And also, pressure, by exerting a downward force, the time comes when it hits here [*under the ball*]. And also, it makes an upward force and the only way/...

3-I: What makes an upward force?

4-S: We did not say it right. We knew it was /

4-I: No but tell me what you [*with emphasis*] think.

5-S: I thought the pressure pushed downward. And because it exerts downward pressure it could not be A because it has never changed shape. And it could not be C either, because if the water was pressing down, it could not be pushed aside because in this drawing C there is sideways pressure. So, I chose B.

5-I: B. So, what about the water...? What do you think...? It pushes on the ball on which side?

6-S: [...] From above.

6-I: From above … .

7-S: And from below, because otherwise it would not be deformed like that.

7-I: From above and from below...?

8-S: Yes.

8-I: And that's why you choose B, right?

9-S: Yes.

9-I: If we have to hold this stone [*we have a stone tied to a rope, a container of water and a dynamometer:* fig. 3], when do we have to use the most force: outside the water or inside the water?

10-S: [...] Inside the water we have to use less force and outside more. Because the water pressure also exerts an upward force which makes this material weigh less.

10-I: It weighs less.

11-S: [...] Sure, picking up the stone outside the water is not the same as picking it up inside because inside there is an upward force.

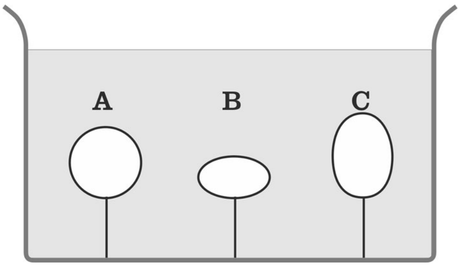
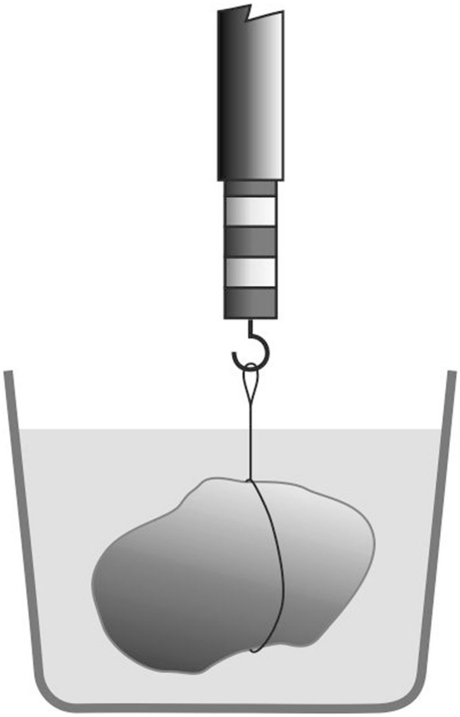


Fig. 2 First physical system considered: spherical ball attached to the bottom of a container filled with water. Students are given three possibilities (A, B, C) regarding what shape it would take on

Fig. 3 Second physical system: a stone in water held by a rope hanging from a dynamometer



11-I: Yes... Before you told me that there is an upward force, but you also told me that there is a downward force.

12-S: Sure [*laughs*], yes... I mean...

12-I: So...

13-S: Well, because there is less force downwards than upwards.

13-I: Upwards...

14-S: There is more force/

14-I: Than downwards.

15-S: OK, so... I do not know how to explain it... [?]

Table 1 shows the codes used in the analysis, and Table 2 contains our analysis of the first extract from the dialogue.

Some points in the dialogue are worth highlighting:

> *3-S.* It seems clear to him that pressure acts downward, so he chose option B: his mental model establishes that a *cause*, downward pressure, produces an *effect*, deformation down. However, he realises that the ball is also deformed below, an effect that needs a *cause*, and therefore, he is forced to admit that pressure also acts upward. To the student, his *mental model* is fully *coherent* and *satisfactory*, regardless of whether it proves to be incorrect from a scientific standpoint.
>
> *4-I.* Since the student is torn between his own way of seeing things and what his class teacher considers correct, the interviewer expresses his interest in knowing his true opinions. He brings the problem (problem 1) to a close by means of *deactivating it*, as it is not an issue of interest for the purposes of the interview.

Table 1 The codes used in the analysis of the dialogue, grouped into columns. The qualifications of emotional states are emphasised

Column: Turn	
number-S	Student's numbered turns
number-I	Interviewer's numbered turns of the interviewer
Column: Dialogue	
[*description*]	Description of actions or significant events
[?]	Speech is hesitant
[...]	Brief pause
/...	Interruption by the other interlocutor
Column: Analysis of the response, detection of ambiguities and generation of the reply	
(M)	After determining the *mental model* that the student seems to be using
(A)	After describing *ambiguities* in the student's mental model
(C)	After evaluating and making strategic decisions about how to *conduct* the dialogue
(L)	After a contribution to communication by *language* means
(P)	After assisting the management of experiments on the *physical system*
(S)	After exploring the *social* consequences of the dialogue
Column: Emotional result and student reasoning	
COH	Student seems to connect causes and effects to understand satisfactorily how the system operates. It is **coherent**
COR	The running of the student's mental model matches the actual behaviour of the system. It is **correspondent**
ROB	The student' mental model of a system also explains unexpected behaviour or others in similar systems. It is **robust**
COH+, COR+, ROB+	Student seems to evaluate the coherency, correspondence or robustness of his mental model **satisfactorily** (emotionally positive)
COH–, COR–, ROB–	Student seems to evaluate coherency, correspondence or robustness of his mental model **unsatisfactorily** (emotionally negative)
property 1 → property 2	Property 1 seems to affect property 2

5-S. This is brief but elaborate reasoning during which he considers different possible mental models in order to discard or accept them. He rules out option A (spherical ball) because the downward force would produce no *effect*, which would make this mental model *incoherent*. He also rules out option C (lateral deformation) because the *cause* (downward pressure) does not correspond to the *effect* (lateral deformation): the mental model would also be *incoherent*. In the end, he accepts option B, apparently because downward pressure (*cause*) creates a downward deformation (*effect*), and so, the mental model is finally *coherent*.

6-S, 7-S. When asked where the ball receives force, he answers using the former mental model: from above (a *cause* that has the *effect* of deforming the ball downward). However, he quickly realises that there is further deformation in drawing B (deformation above and below), an *effect* that has no *cause*. At that time, he realises that his *mental model* has just lost its *coherency* and immediately resolves this by seeking a new *cause* for an unexplained *effect*: there is deformation below because pressure is exerted from below in addition to from above. The model has regained its *coherency*.

Table 2 Analysis of the first extract from the dialogue between the interviewer and a student. (Different functions are shown in each column, as described above)

Turn	Dialogue	Analysis of the response (M), detection of ambiguities (A), and response generation	Emotional result and student's reasoning
1-I	In this case [Fig. 2: *ball submerged*], this ball is attached to the bottom. What did you think? That it would end up like A, B or C?	(The interviewer presents the situation to be solved and asks the student to make a prediction) (C).	
2-S 2-I	Like B. Like B. Why?	We do not know the reason (*cause*) why he chooses B [*ball flattened above and below*] (A).	(Prediction without justification)
3-S 3-I	Because [...] force or pressure is exerted downward. And also, pressure, by exerting a downward force, the time comes when it hits here [*under the ball*]. And also it makes an upward force and the only way/... What makes an upward force?	Pressure appears as an *entity*, with the *property* of exerting force. Downward force and upward force would be the causes of the twofold deformation of the ball in case B (M). He does not clarify where the forces come from (A).	COH+ downward F and upward F ➡ double flattening
4-S 4-I	We did not say it right. We knew it was/ No but tell me what you [*with emphasis*] think.	He is repeating what the teacher said in class, without sharing it or understanding it. The conversation should focus on their own opinion (C).	COH– in class: ? *he*: different
5-S 5-I	I thought the pressure pushed downward. And because it exerts downward pressure it could not be A because it has never changed shape. And it could not be C either, because if the water was pressing down, it could not be pushed aside because in this drawing C there is sideways pressure. So, I chose B. B. So, what about the water...? What do you think...? It pushes on the ball on which side?	Once again, pressure is an *entity* with the *property* of straining. However, he associates deformation with force (or pressure, because they seem synonymous to him). It seems clear to him that pressure acts downward and the deformation would go down (M). Yet earlier, he mentioned an upward force, but not now (A).	COH+ downward force ➡ deformation down COH+ no lateral force ➡ no lateral deformation
6-S 6-I	[...] From above. From above …	Force only comes from above (M). Deformation of lower part remains unexplained (A).	COH+ force from above ➡ deformation of upper part
7-S 7-I	And from below, because otherwise it would not be deformed like that. From above and from below...?	Rectifies: considers that the deformation of lower part must have a cause: the pressure from below. So, there is pressure above and below (M). Statement to be confirmed (L).	COH+ pressure above and below ➡ deformation of upper and lower parts
8-S 8-I	Yes. And that's why you chose B, right?	It is not entirely clear whether he really relates it to the deformation (A). Statement to be confirmed (L).	(Same mental model)
9-S 9-I	Yes. If we have to hold this stone [*we have a stone tied to a rope, a container of water and a dynamometer*: Fig. 3], when do we have to use the most force: outside the water or inside the water?	It looks that way (M). We will suggest that he analyses a new problem (C). The wording tries to avoid saying that the weight changes (L).	(Agreement)

Table 2 (continued)

Turn	Dialogue	Analysis of the response (M), detection of ambiguities (A), and response generation	Emotional result and student's reasoning
10-S	[...] Inside the water we have to use less force and outside more. Because the water pressure also exerts an upward force which makes this material weigh less.	The claim that less force is required suggests that he knows the phenomenon and uses it as evidence to find the cause (M).	COR+ upward P ➡ weight reduction
10-I	It weighs less		
11-S	[...] Sure, picking up the stone outside the water is not the same as picking it up inside because inside there is an upward force.	The answer is probably *correspondent* (M), but now the pressure goes up and he does not mention the pressure downwards, which he mentioned earlier (turn 7-S), or what causes upward force but surely it is water, just as he also stated in turn 7-S as well (A).	(Same mental model)
11-I	Yes... Before you told me that there is an upward force, but you also told me that there is a downward force.		
12-S	Sure [*laughs*], yes... I mean... [?]	He realises that it does not make sense and laughs: the upward force makes it weigh less, but the downward force should make it weigh more; there is no coherency (M): Will it weigh more or less? (A)	COH– upward F ➡ weight decreases downward F ➡ weight increase
12-I	So...		
13-S	Well, because there is less force downwards than upwards.	He solves the problem by making one force greater than the other, probably because he is familiar with the phenomenon. It is now *correspondent* again, and *incoherency* is resolved (M). To check this, an incomplete sentence (L) is uttered.	COH+ small downward F and great upward F ➡ less weight COR+ Matches the experience
13-I	Upwards...?		
14-S	There is more force/	He completes it *coherently* (M). To complete the check (A), a statement to be confirmed (L) is uttered.	(Same mental model)
14-I	Than downwards.		
15-S	OK, so... I do not know how to explain it... [?]	We interpret the lack of response as confirmation (M). But he expresses doubt as to the reason for this difference in forces (A).	COH– cause? ➡ small downward F and greater upward F

This brief episode shows the need for students to have *satisfactory* mental models and the priority of changing them when they are not very clearly. Apparently, this need far outweighs their attachment to existing mental models.

12-S. In his analysis of the student's answer, the interviewer has noticed an *ambiguity*: first (turn 7-S), the student said that water exerted force upward and downward on other submerged object (a ball), and he believes that this flattens it vertically, while now he only mentions the upward force. He reacts by laughing, an *emotional* expression, indicating that he is experiencing *dissatisfaction* with his own mental model, which leads him to infer that the object should weigh more... and simultaneously less: an impossible fact that prevents him from building his *causal model* (because of a lack of *coherency*), which drives him to review the entities and their properties immediately.

The student's laughter when his model is in crisis can only occur in a non-threatening and collaborative school environment (Ardashevaa et al. 2015).

> *13-S*. He solves this by stating that the upward force is greater than the downward force. Now the *mental model* is once again *coherent* and, as it provides him with the empirically correct inference (he knows that the object appears to weigh less), it also becomes *correspondent* and is fully *satisfactory*.
> *15-S*. He does not seem to find a reason why upward and downward forces are different. Since he can no longer build the appropriate causal chain, the model now seems *incoherent* to him and therefore *unsatisfactory*. This causes a problem (problem 2) which is detected by the student in turn 12-S, which will be present for most of the interview and will not be settled until turn 113-S, when he finds a *satisfactory* solution.

Extract 2: Turns 109-I to 114-S

The dialogue subsequently focuses on the pressure inside a liquid. Several experiments are conducted (Fig. 4), which show that pressure only depends on the depth and is indifferent to the direction measured.

Spontaneously, the student once again focuses the dialogue on the ball in Fig. 3, showing his discomfort with the experiment's results. The difficult is solved shortly after (see this part of the dialogue and its analysis in Table 3):

> 109-I: So, what would happen to the ball?
> 110-S: [...] It would be round, but smaller.
> 110-I: It would be crushed on all sides and would stay round but be smaller...
> 111-S: Yes, in theory... [?]
> 111-I: In theory... So, the right answer would be neither A nor B nor C.
> 112-S: [...] According to this experiment, no [*laughs*]
> 112-I: According to this experiment, no... Except A is already...
> 113-S: Smaller/

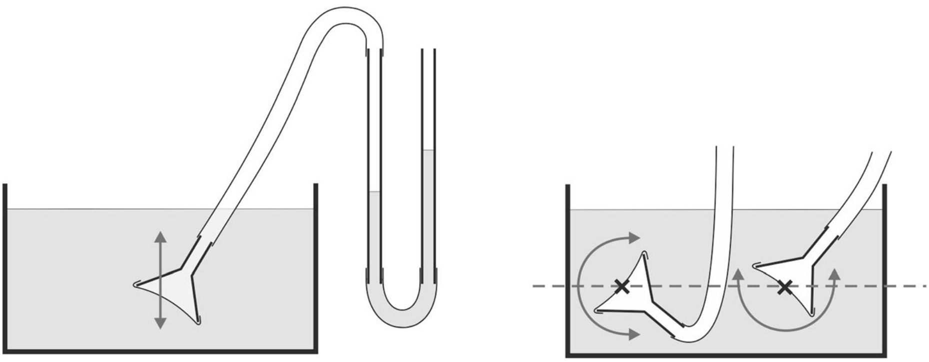


Fig. 4 On the left, the device for studying pressure inside the liquid is shown, proving that the deeper it goes, the higher the pressure detected is (the water unevenness between the two tubes increases). On the right, using the same device, the movement of the funnel is shown, and it is rotated around one of the diameters of its mouth to show that the pressure does not vary according to the direction

Table 3 Analysis of extract 2 from the dialogue between the interviewer and the student

Turn	Dialogue	Response analysis (M), detection of ambiguities (A) and response generation	Emotional result and student's reasoning
109-I	So, what would happen to the ball?		
110-S 110-I	[...] It would be round, but smaller. It would be crushed on all sides and would stay round but be smaller...	Pressure in all directions deforms the ball everywhere equally (M). Statement to be confirmed (L).	COH+ P in all directions ➡ deformation in all directions
111-S 111-I	Yes, in theory... [?] In theory... So, the right answer would be neither A nor B nor C.	Confirms it (M) but seems to doubt the outcome, perhaps because on giving up option B (in Fig. 3), it is not clear to him which of the three options will be the correct one (A). Statement to be confirmed (L).	(Uncertain)
112-S 112-I	[...] According to this experiment, no [*laughs*] According to this experiment, no... Except A is already...	Confirms it (M). Perhaps laughter is a sign that he realises that none of the options was correct. We try to make him aware of the possibility of reinterpreting one of them (A). Phrase to complete (L).	COH– options offered: none is right
113-S 113-I	Smaller/ Smaller than it was before. Right?	True. He can restore coherency by thinking that the original ball was larger than the one in drawing A (M). To check it (A), a statement to be confirmed (L) is uttered.	COH+ P in all directions ➡ round but smaller
114-S	[*Laughs*] Imagine that!	We interpret the lack of answer as meaning yes. Again, laughter seems to show surprise at an unexpected solution (M).	COH+ options offered: one right option

113-I: Smaller than it was before. Right?
114-S: [*Laughs*] Imagine that!

110-S. The result of the experiment, which shows that pressure acts equally in all directions, converts his previous model (7-S) to *non-correspondent*, so he is forced to replace it with another: the pressure all around (*cause*) will deform the ball in all directions, making it smaller (*effect*). The model has become *coherent*. Because of the lack of experimental data, neither *correspondence* nor *robustness* can be evaluated.
113-S. So far, he has interpreted that there was no deformation in option A (Fig. 2). Now he reinterprets it by thinking that the original form was larger and that in A, the ball has got smaller without changing its initial shape. The model is now definitely *satisfactory*, and problem 2 has been solved.

Extract 3: Turns 141-I to 155-S

After a while the dialogue returns to the weight of a submerged object.

141-I: What forces...? Water, what force does it exert on this [*this weight*]? Upward? Downward? To the right? To the left...?

142-S: [*Laughs*] Everywhere.

142-I: Everywhere... But we have seen that this force was not the same everywhere. It depended on something...

143-S: [...] The depth.

143-I: The depth... So, are all the forces it receives equal?

144-S: Yes.

144-I: Are the right and left forces the same...? Are the top and bottom ones the same...?

145-S: Yes, they are.

145-I: Are they equal...?

146-S: Yes.

146-I: Are they at the same depth...?

147-S: [...] At the same depth, no!

147-I: Oh, no...?

148-S: No, because the bottom one is deeper than the top one.

148-I: So...?

149-S: So, it means that the lower ones exert more pressure than the upper ones.

149-I: So...?

150-S: That means that they are exerting more upward pressure than downward. So, for that reason... this weight [*the experimental weight*] [...] weighs less in [*the water*] than out.

150-I: It seems... to weigh less, right...?

151-S: It seems to weigh less, but it weighs the same.

151-I: Because in fact, you are holding the weight [*out of the water*], but when you put it in the water...

152-S: The water helps you because it exerts upward pressure.

152-I: Water also helps you hold it a bit... does not it?

153-S: [*He laughs*]

153-I: What...?

154-S: Well, when I take the exam...

154-I: You may score a perfect 10 [A^+], right?

155-S: Right [*He laughs*]

The analysis of this extract is shown in Table 4:

142-S. He now applies what he learnt about pressure from the funnel experiment to the submerged ball, changing the old version and thus providing *robustness* to his new model.

144-S, 145-S. The forces in all directions are all the same to the student, as the experiment with the funnel seems to have shown. Although scientifically incorrect, from his standpoint, everything is perfectly *coherent*, so he feels no need to change anything.

147-S to 150-S. By insisting on the depth, he suddenly realises that the upper and lower parts of the object are not at the same depth (different *causes*). This makes him change his mental model to incorporate this difference, which causes differences in the forces (different *effects*) and provides an explanation for the submerged stone's apparently lower weight (*coherency*), which he knows is real (*correspondence*). The student's mental model is now *satisfactory* and finally compatible with the scientific model, solving problem 3.

153-S to 155-S. Having clarified the three relevant problems, he is pleased because he will be able to explain everything to his classmates (a condition imposed on him by his teacher) and he laughs again.

We can therefore see from these extracts that the student's learning effectively progresses by his constructing and reconstructing satisfactory mental models for the proposed physical systems. When a model is no longer *satisfactory* to him, it immediately goes into crisis and he tries to introduce changes to make it satisfactory again. The process is

Table 4 Analysis of extract 3 from the dialogue

Turn	Dialogue	Response analysis (M), detection of ambiguities (A) and response generation	Emotional result and student's reasoning
141-I	What forces...? Water, what force does it exert on this [*this weight*]? Upward? Downward? To the right? To the left...?	The issue regarding the case of the submerged ball got stuck at 33-A because of a lack of *robustness* (M), given that it received pressure from both above and below (A). Can he specify the relationship according to what he has been learning? (C).	
142-S 142-I	[*Laughs*] Everywhere. Everywhere... But we have seen that this force was not the same everywhere. It depended on something...	He probably laughs because he has changed his explanation of the system by introducing lateral forces. In contrast to the situation at the beginning, it is now clear that pressure acts in all directions (M). He does not now explain the apparent weight loss. He has to be reminded that the effect was not the same in all directions in his model, and now he can be asked the cause (A).	ROB+ Funnel: P equal in all directions. Stone: P equal in all directions
143-S 143-I	[...] The depth. The depth... So, are all the forces it receives equal?	Things are going well (C). The effect of depth on pressure (M) is clear to him. Can he apply it to the forces exerted on the submerged stone? (A)	COH+ Greater depth ➡ greater P
144-S 144-I	Yes. Are the right and left forces the same...? Are the top and bottom ones the same...?	He applies the rule that the pressure does not depend on the direction, but he does not realise that there are different depths (M). Will he realise whether or not pairs are offset (A).	COH+ Different directions ➡ same P
145-S 145-I	Yes, they are. Are they equal...?	He continues to believe that the pressure does not depend on the direction (M). Surprisingly, he does not realise that the depth changes (A). This point will have to be stressed (C).	(Same mental model)
146-S 146-I	Yes. Are they at the same depth...?	He believes that there are identical effects (A). He will have to be asked whether the causes are also identical (A)	(Same mental model)
147-S 147-I	[...] At the same depth, no! Oh, no...?	Now he realises that there are different depths (M). We must try to get him to verbalise what he is paying attention to when he says that the depth is different (A).	(Attention to a property)
148-S 148-I	No, because the bottom one is deeper than the top one. So...?	He has paid attention to a difference (M). Can he give its effect? (A)	(Same mental model)

Table 4 (continued)

Turn	Dialogue	Response analysis (M), detection of ambiguities (A) and response generation	Emotional result and student's reasoning
149-S 149-I	So, it means that the lower ones exert more pressure than the upper ones. So...?	In the end he explains why the forces above and below are different (M). Can he relate this with the stone's apparently lower weight? (A)	COH+ Bottom surface ➡ greater depth ➡ greater force
150-S 150-I	That means that they are exerting more upward pressure than downward. So, for that reason... this weight [*the experimental weight*] [...] weighs less in [*the water*] than out. It seems... to weigh less, right...?	Now he satisfactorily completes the chain of inferences (M). Will he realise that the weight has changed? (A) Statement to be confirmed (L). Warning about how to express this (L).	COH+ Bottom surface ➡ greater depth ➡ greater pressure upward than downward ➡ lower apparent weight COR+ *Theory*: it must weigh less *Fact*: it weighs less ROB+ *Funnel*: further down ➡ greater pressure *Stone*: greater pressure below than above ➡ weighs less
151-S 151-I	It seems to weigh less, but it weighs the same. Because in fact, you are holding the weight [*out of the water*], but when you put it in the water...	He does rectify his formulation. Weight change is not real but apparent (M). He seems to understand why, but he does not fully realise the cause of the apparent decrease in weight (A). Sentence to complete (L).	COH+ *In water*: equal weight and pressure difference ➡ it seems to weigh less
152-S 152-I	The water helps you because it exerts upward pressure. Water also helps you hold it a bit... does not it?	We now have the cause (M). We must ensure that he understands it (A) by proposing a statement to be confirmed (L).	COH+ The water pushes it up ➡ it seems to weigh less
153-S 153-I	[*He laughs*] What...?	We interpret the lack of explicit response as positive. The laughter seems to indicate that things are finally falling into place (M).	(Agreement)
154-S 154-I	[...] Well, when I take the exam... You may score a perfect 10 [A+], right?	He seems to indicate that when he explains it in class there will be surprises like the ones he himself has encountered, but then he will have to convince his peers. With everything he has achieved in this conversation, he is sure he will do it well and get a good mark (S).	(Social)
155-S	Right [*He laughs*]	He shows satisfaction. We end the interview with this (C).	(Social)

based on the evaluation of the *coherency*, *correspondence* and *robustness* of mental models, which is closely related to positive and negative emotional states vis-à-vis his mental model.

The Interviewer's Regulatory Tasks

The reflections recorded in the column 3 of the tables show how the interviewer performs six tasks during the dialogue (corresponding to the codes in brackets in Table 1) which are grouped into three broad regulatory functions:

Evaluating

(M) This consists of creating a similar model to the student's *mental model* in his own mind from the student's explanations and evaluating it—always according to the pupil's viewpoint—to discover whether or not the student considers it *coherent*, *correspondent* and *robust*.

Stimulating

(A) The interviewer aims to discover *ambiguities* in the student's mental model in order to ask him about them. Disentangling ambiguities is a psychological necessity for the student, which drives him to reconstruct his mental model and thereby improve it.

Other Regulations

(C) Evaluations and decisions about how to *conduct* the dialogue: deciding whether a given path of inquiry is over, trying another strategy, changing the system to be analysed, saving a question for later, etc.

(L) *Language* strategies to contribute to the dialogue's progress; for example, making a statement that the student must accept or change, consciously choosing certain forms of speech, etc.

(P) Management of experimental interventions on the *physical* system.

(S) Considering the *social* consequences of the dialogue.

Thus, the *teachback* technique has enabled us both to conduct and regulate the course of the dialogue and analyse it subsequently in an educationally productive interview.

It is worth highlighting that our theoretical framework accounts for all the data collected, without generating residual data. Thus, both the framework and the symbols created to handle it are shown to be effective tools for conducting and analysing educationally productive dialogues between teacher and student.

Usefulness of the *Teachback* Dialogue

What was achieved in the course of a dialogue conducted using *teachback*? Mainly the following: (a) some of the student's emotional reactions (satisfaction or dissatisfaction) with respect to learning, which can lead to the reconstruction of mental models that the student considers unsatisfactory, were highlighted; (b) the fact that the student had learned some aspects of a scientific model correctly was verified.

Emotions and Learning

When the student realises that the model he has in mind lacks coherency, correspondence or robustness, he is affected psychologically and experiences negative emotional states.

Something similar happens if he thinks that his model is coherent, correspondent and robust; but in that case, there is an equilibrium between his psychological state and what he observes in the world, and he experiences a positive emotional state. Emotional reactions appear while evaluating mental models, whether they become satisfactory or unsatisfactory (Damasio 2018). Moments of real learning are therefore periods of noticeably heightened emotions.

Science Learning

Five problems emerged during the 18-min dialogue, two of which were immediately solved for various reasons (1 and 5), while the other three required dozens of exchanges between the interviewer and the student—including experimenting with physical systems and the study of other systems—before they were properly solved. Figure 5 represents the evolution of the five problems, and three of them (2, 3 and 4), which are represented with thick grey lines, take longer. Only problems 2 (What is the direction of pressure in water?) and 3 (Why does the stone seem to weigh less in water?) are addressed in the extracts of the dialogue analysed in this paper (problem 1—the student's disagreement with regard to his teacher's statements—was quickly overcome):

If we focus on the problems the student detects in turns 12-S and 15-S, the various reconstructions of his mental model as he tries to resolve them are summarised in Table 5. This is a brief summary of the student's interventions analysed, together with some inferences related to resolving problems 2 and 3. The student initially considers them in turns 12 and 15 ("start") and does not consider them to be finally resolved until 113 and 152 ("end").

We should note that the student ended up by giving a scientifically correct explanation for all three long-term problems he encountered in the dialogue, without the interviewer providing it either directly or indirectly. The student overcame all the difficulties he encountered by himself (self-learning) (Bodomo and Hu 2011; Kolstø 2018; Tscholl and Lindgren 2016).

It should be noted that both the interviewer and the student engaged in the *teachback* dialogue reported, after the dialogue, feeling natural and agile at all times. This is the only explanation for 155 turns per speaker in 18 min, their productivity in analysing the proposed systems and their using the systems to solve three problems, which were not at all obvious to the student, satisfactorily and scientifically.

There is no doubt that each of the student's unsatisfactory mental models causes a problem that he needs to solve as soon as possible, because until he does so the positive emotion associated with learning will not be created. This serves as an emotional reward, acts as genuine motivation and potentially enhances student's self-concept (Cheung 2018).

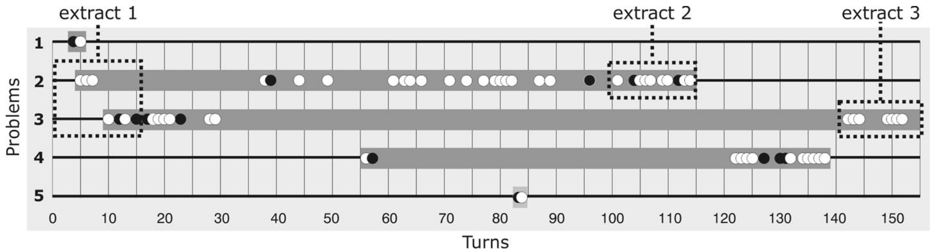


Fig. 5 Evolution of the five problems. The 69 circles are located at the turns in which 83 emotional results are generated while trying to detect and resolve the problems. Unsatisfactory results are indicated by black circles, while white circles indicate satisfactory ones. If a turn has presented different emotional results, it is marked only as negative. The three parts of the dialogue discussed in this article are indicated by dotted boxes

Table 5 Summary of the student's interventions analysed, together with some inferences related to resolving problems 2 and 3. The arrows indicate that the problem has not been completely solved yet

Turn	Satisfactory inferences	Unsatisfactory inferences	Remaining problem	Mental model description
12		COH–	2 Start	Water exerts a force upward and downward
13	COH+		2 ↓	Water exerts greater upward force than downward
13	COR+		2 ↓	Matches the experience
15		COH–	2 ↓	We do not know what causes the upward force to be greater than the downward
96		ROB– COR–	2 ↓	Equal force in all directions. In another case: above and below
101	COR+		2 ↓	Same pressure in all directions
104		ROB–	2 ↓	Same pressure in all directions. Uneven deformation in another case
110	COH+		2 ↓	Force in all directions. Deformation in all directions
112		COH–	2 ↓	Options offered in the dossier. Right choice
113	COH+		2 End	Reinterpret one of the options offered
15		COH–	3 Start	What causes the water to exert more upward force than downward?
17		COH–	3 ↓	It is not gravity, because it acts inside and outside the water
23		ROB–	3 ↓	Ball: upward and downward force. Stone: upward force
142	ROB+		3 ↓	Funnel and stone: P equal in all directions
143	COH+		3 ↓	Stone: greater depth, greater pressure
149	COH+		3 ↓	The bottom surface receives more pressure than the upper one
150	COR+		3 ↓	It should weigh less. We have recorded a lower weight
150	ROB+		3 ↓	Case of the funnel. Case of the stone
151	COH+		3 ↓	It weighs the same, it seems to weigh less
152	COH+		3 End	Water helps by exerting upward pressure

Making scientifically correct inferences by themselves, without added external information, is a stimulating and emotionally positive experience that can be decisive for students' involvement in their own learning, especially in science. According to a hypothesis set out for the ONEPSY model, this is related to an intrinsic motivation mechanism for learning.

Discussion

Taking these results into account, the paper now aims to examine some of the aspects considered crucial for modelling in science education, but which have posed major difficulties in practice, as many studies have found.

How to Regulate the Construction of Satisfactory Mental Models?

To regulate the construction of satisfactory mental models, we need to understand the mechanisms that are effective for achieving this end, especially their dynamics.

It can be seen from specific literature in the field that different authors propose slightly different *cycles* when describing the dynamics of model construction. The cycle proposed by Schnotz et al. 1999 in their thoughtful 2009 paper appears to have been cited by highest number of researchers engaged in the task of building scientific knowledge by means of models or modelling perspectives (i.e. Bamberger and Davis 2013; Jong et al. 2015; Nelson and Davis 2012, and Garrido and Couso 2015). In their paper, Schwarz et al. present their cycle as follows:

> Building on prior work on epistemologies and the nature of science, we have operationalized the practice of modelling to include four elements that we target: Students *construct* models; *use* models; *evaluate* models; *revise* models (p 635) (authors' emphasis).

The cycle is thus supported by the beliefs that this is the way that scientists construct scientific knowledge:

> Involving learners in modelling practices can help them build subject matter expertise, epistemological understanding, and expertise in the practices of building and evaluating scientific knowledge (p 633).

How Is the Iteration of Cycles Maintained?

This is the key factor in the processes of constructing and reconstructing models until the student arrives at the desired learning result: once a cycle is complete and a model has been built, what is the driving force (motivation) that impels the student to follow on with iterative cycles of constructing and reconstructing models?

While other authors do not seem to address this question, Schwarz et al. do face the problem, and their answer is as follows:

> The metaknowledge... guides and motivates the practice (e.g., understanding the nature and purpose of models) (p 632).

It is difficult to find authors that think critically about the elements pointed out by Schwarz et al. 2009 However, Schwarz et al. 2009 themselves give an account of the results of implementing their model in the classroom and also discuss the difficulties. Thus, in the Discussion and Conclusion sections of their paper, they say:

a. With regard to model construction:

> Several challenges emerge... First... In the case of our classroom materials, students are typically told when to create models... A second challenge... for the most part, students seemed to see their own models as being created for the teacher as just another form of 'science answer'. They did not typically try to make a model to facilitate their own thinking or their own communication of ideas (p 652).

It would seem difficult to work solely within epistemological approaches. Psychology is a main point in spontaneous thinking and learning and the ONEPSY model can be useful here.

b) With regard to motivation:

> A third challenge is in motivating the need to revise model... the class was always told to revise their models (p 652).

The ONEPSY model shows a simpler cycle and openly demonstrates the intrinsic mechanism that maintains motivation for recursive constructing and reconstructing of models: the psychological need for thought to be in agreement with itself and with the world.

Studies such as Rea-Ramirez (2008), Ford and Wargo (2012), Campbell et al. (2012) and Mendoça and Justi (2013) propose *teacher interventions* that provide "dissonance" or "violation of expectation" (Valdesolo et al. 2017) to encourage students to improve their models. From the perspective of the framework proposed by the ONEPSY model, teacher interventions should be interpreted as contributions that help students generate their own feelings of dissatisfaction, not ready-made dissatisfaction that comes from outside. Students ought to evaluate their own mental models on the basis of their internal reasoning mechanisms.

Are Regulation Cycles Frequent?

In one study Kahn (2007), p. 895) detected an average of two mental model evaluation and modification cycles per class. Our data are very different: in the full 18 min that the interview lasted, there were at least 83 evaluations (Figs. 5 and 6) of mental models, with their corresponding emotional states: 69 of the 83 emotional states were found to be satisfactory and 14 were not (Fig. 6). Each of the 14 unsatisfactory evaluations pushed the student to modify his mental model until it was satisfactory, a process that acts as intrinsic motivation.

According to the above data (Fig. 6), in the dialogue studied, reconstruction was necessary roughly once every six times (83/14 = 5.9) a mental model was evaluated. We believe that this disproportion in favour of satisfactory evaluations is educationally positive for students: firstly, more positive evaluations help them to generate a relatively comfortable sense of security and interest (King et al. 2015), while a small but significant number of unsatisfactory evaluations are necessary to trigger the process of reconstructing the mental model, i.e. of learning, culminating in a successful final self-evaluation.

Discrepancies between our data and Kahn's may be due to methodological differences. The fine grain analysis that *teachback* dialogue provides allows the researcher to detect how the student's mental model is continuously being tested and therefore how it may be reconstructed as many times as needed. From a more simplified viewpoint, the interview analysed can be described as being simply the process of resolving the three relevant problems, but the cognitive activity that makes this possible is richer and more complex and has the advantage of showing us exactly what triggers the student's learning.

The ONEPSY model seems to bring about a substantial improvement in the capacity for analysing dialogues, from which it is possible to benefit in an educational sense.

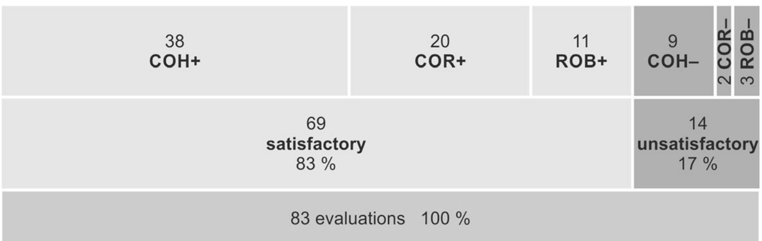


Fig. 6 Emotional results of the mental model evaluations

What Are the Interviewer's Basic Tasks?

As Russ et al. (2012) suggest, to facilitate the construction of knowledge through dialogue, it is crucial to avoid turning a conversation with students into an interrogation or oral exam and to treat students as experts in their own ideas instead. In the same vein, for classroom dialogue to work properly, it is essential to create the right positive, non-threatening tone or emotional climate (Andersen and Nielsen 2013; Ardashevaa et al. 2015; Bellocchi et al. 2014) which accepts mistakes as a necessary part of learning (Kawasaky et al. 2004; Pereira et al. 2016). Only in this way will students dare to share their opinions, even though they are often not entirely sure. Reaching *unsatisfactory* mental models is less painful (and even stimulating, as we saw when the student laughed) if it is part of the rules of the game.

Some authors have examined the basic tasks that teachers should carry out when trying to maintain the dynamic of model construction and reconstruction until the proposed learning targets have been achieved (i.e. Kahn 2007). Williams and Clement (2015) appear to give the most thorough description of such strategic tasks. They prefer to speak not of students' model construction, but of *co-construction*, because teachers' specific instructions and the data provided to the students form part of such strategies. These authors' theoretical framework was a model-based reasoning view of scientific practice (epistemology-based), coming from expert cognitive science studies. This forms the basis of a dynamic process which they called GEM cycles (model generation, evaluation and modification cycles).

Their findings are summarised in the Conclusion section of their paper as follows: (a) they found four *macro-strategies*, each corresponding to the GEM cycles, and one more related to "observations"; this was necessary "for the purpose of bringing the attention or memory of the participants to the phenomenon being discussed" (p 88). (b) They also identified 39 micro-strategies. Macro- and micro-strategies are related: "we found that each of the strategies at the micro level could be interpreted as a sub-strategy or sub-process operating in the service of one of the OGEM processes at the macro level." (p 100). Bearing in mind the difficulties teachers can experience when managing this number of strategies, Williams and Clement point out: "Realizing that 39 micro strategies at the cognitive model construction level was too large a number to expect science teacher educators to address and teachers to remember and make meaningful use of in classrooms, we sought to amalgamate these into a more manageable number" (p 90). Therefore, they merge the 39 micro-strategies into 15 (descriptions on pp. 91–92).

The number of regulatory tasks found by the authors is likely to be due to the lack of a more adequate theoretical framework to support fine grain dialogue analysis. If these numbers are compared with the six basic regulatory tasks that the teacher performs in *teachback* dialogues, described above in "The Interviewer's Regulatory Tasks", the advantages of having a theoretical model that facilitates and simplifies the task is clear.

How Is Convergence Towards the Scientific Model Possible? The Continuous Hypothesis

It is difficult to deny that by starting from models constructed on the basis of commonsense, students can manage to construct scientific knowledge. Many authors report this achievement on the basis of empirical data (i.e. all those quoted in this paper, based on model constructing and reconstructing cycles). However, a problem arises from this: what about incommensurability between common sense knowledge and scientific knowledge?

This is an open debate in the philosophy of science field (i.e. Brown 2005; Green 2016; Hoyningen-Huene 2013), and as previously mentioned, it is important for explaining the fact that students make real gains in scientific knowledge on the basis of very simple mental models.

Nancy Nersersian has studied this problem for many years (from 1984 at least). Her main claim is that to know how scientists construct knowledge it is necessary to study the *context of discovery* instead of the *context of justification* (Reichenbach 1938). As a result of her research, she developed a method called *Cognitive Historical Analysis*, CHA, explaining that "The underlying presupposition [of-CHA] is that the problem-solving strategies scientists have invented and the representational practices they have developed over the course of history of science are very sophisticated and refined outgrowths of ordinary reasoning and representational processes" (Nersessian 1992, p 5). Later she openly faced the problem of incommensurability: "I argued that these philosophical problems are artefacts of the framing of change, in a way that just compared the end point of a long process, and did not take into account the fine structure in between" (Nersessian 2008, p x); and set out the Continuous Hypothesis: "Cognitive science investigations aid in aligning these practices with those that non-scientists use to solving problem and make sense of the world (…). Scientists use has developed out of these ordinary human cognitive capabilities ("Continuous Hypothesis"), and thus research into these problem-solving heuristics by cognitive science provides resources to tackle the more elaborated and consciously refined usage by scientists" (idem p xi).

Some authors invoke the Continuous Hypothesis to justify the designing of learning sequences on the basis of spontaneous mental models and developing them by means of construction and reconstruction cycles until the target scientific model is achieved (Svoboda and Passmore 2013; Tumay 2016); many others take the solving the problem for granted and simply affirm the continuity of commonsense knowledge to scientific knowledge (Wu 2010; Giere 2010; White et al. 2011).

The Continuous Hypothesis appears to reinforce and guarantee the usefulness of the ONEPSY model together with the *teachback* technique for the design of learning sequences, as shown in an extensive work (Aliberas 2012), which cannot be reported here.

Conclusions and Prospects

In relation to its three objectives, this paper has shown the following:

(1) The ONEPSY model has been especially useful in developing the method of analysing and conducting didactic dialogues that facilitate students' development of scientifically valid inferences.

(2) The method of analysis used has revealed the processes that occur during a didactic dialogue regulated by *teachback*. These processes have proved to be more numerous and complex than those usually described in educational literature. They are also natural and manageable for both participants.

(3) We have shown the usefulness of *teachback* regulation, focusing it on the ambiguities in the student's mental models, as inferred from his explanations. This was crucial to getting him to overcome the major learning difficulties encountered and eventually using scientifically correct reasoning, which amply justifies the time and effort spent. The

teacher also has to perform different tasks to regulate didactic dialogue and create a positive emotional climate in the conversation.

Some of the most important issues that future research in this field could address are raised below.

Use in a Group

Teachback dialogue is not only useful in individual encounters between teacher and student, it can also be useful to establish these dialogues between the teacher and a group, with the same aim of reaching a final consensus, this time with all the students. We have carried out some classroom experiences (Íñiguez and Aliberas 2015) which produced very promising results, and the mechanisms and results are very similar to those obtained in this study. The difference is that the teacher then has another regulatory task: managing the participation of the whole group. This task is certainly worth undertaking.

Development of Teaching Sequences

The *teachback* dialogue examined could not possibly succeed without proper planning of the physical systems studied and the problematic aspects that students are expected to encounter in them (i.e. it is necessary to know about previous students' spontaneous thinking on the topic, and this has been widely studied in the literature). Some authors have developed teaching sequences taking into account all the necessary precautions we have discussed when carrying out *teachback* conversations (Gutierrez 2017; Íñiguez and Aliberas 2015; López-Mota et al. 2016). However, we feel that there are still insufficient controlled results from the implementation of these works. Nevertheless, as mentioned, all these authors report increased motivation, participation, excitement, etc. among students and the consequent creation of a classroom atmosphere that significantly facilitates the path from spontaneous thinking to the construction of scientific knowledge. Controlled experimentation on this point is therefore another challenge waiting to be met.

Finally

At a time when one of the main problems in education is lack of student motivation and effort, we believe that this avenue of research is particularly promising.

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