ISSN 1648-3898

PATHWAYS OF STUDENTS' CONCEPTUALISATION DURING A PROBLEM SOLVING TASK: LESSONS FOR TEACHING PHYSICS

Abstract. *This study aims to characterise the pathways of students' conceptualisation during a problem solving task in order to understand the role of conceptualisation in conceptual learning and to identify salient points for the practice of teaching physics. The study took place in a Portuguese classroom with 15 physics students, all aged 17. The "global conceptualisation" emerged from this research as an important construct to explain how students mobilise their conceptual knowledge during a problem solving task Six other salient characteristics of the pathways of students' conceptualisation were also identified. In addition, some conditions related to teaching which could help to improve students' conceptualisation and conceptual learning were also uncovered. These results are discussed and are presented alongside conclusions about the focus and direction of teacher intervention.*

Key words: *conceptualisation pathway, modelling, problem-solving, physics education, teaching.*

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Introduction

This study aims to characterise the pathways of students' conceptualisation process during a problem solving task in order to understand the role of conceptualisation in conceptual learning, and in order to identify points that are relevant to teaching physics. The relationship between conceptualisation and scientific learning is an important issue in scientific education, and has been studied by several authors (e.g. Borges & Gilbert, 1999; Clement, 2000; Greca & Moreira, 2000; Taylor, Barker, & Jones, 2003). However, we are interested in understanding the process of how students cognitively represent complex physical phenomena and the pathways that different groups of students follow in the process of achieving a higher level of understanding of a particular problem in physics. Currently, these issues are not widely studied (Clement, 2000). Any attempt to use physical knowledge in reference to a problem task requires students to idealise, simplify, conceptualise and/or describe the problem. This implies that there is an interconnection between the internal and external representations (Toth, Suthers, & Lesgold, 2002). Representation, as a mental model (Greca & Moreira, 2000; Norman, 1983), is therefore a guide for the student's actions and thoughts, particularly in the personal domain. This activity of representation should progressively materialise in public forms of communication within the classroom, referred to as "external representation" (Toth et al., 2002). Representation may, in particular, provide a way of describing a physical situation, taking into account the problem which must be solved; such descriptions then become the objects of reasoning (Vergnaud, 1991). The research regarding the need for representation in problem-solving in physics is largely documented' (e.g. Chi, Feltovich, & Glaser 1981; Larkin, 1983; De Jong & Ferguson-Hessler, 1991). In general, learning about physics also requires a qualitative approach towards problems (e.g. Dumas-Carré, Goffard, & Gil-Perez, 1992; Stinner, 1995; Leonard, Dufresne, & Mestre, 1996; Van Heuvelen, 1991) and context-rich problems (Heller, Keith, & Anderson, 1992; Heller & Hollabaugh, 1992).

Recent literature has emphasised the role of problem solving in conceptual understanding (Gaigher, Rogan, & Braun, 2007) and the role of conceptual understanding in problem solving (Hung & Jonassen, 2006). This relationship is not simple, because students who better perform in terms of their conceptual understanding obtain the same or slightly worse results when solving quantitative problems in their final exams than students with poorer conceptual understanding (Hoellwarth, Moelter, & Knight, 2005). One the other hand, some literature has stressed the importance of students' structured collaboration in solving physics-related problems (Harskamp, & Ding, 2006) or the importance of intuitive knowledge in problem solving in physics (Sherin, 2006).

The purpose of this research is to contribute to the understanding of the process of students' idealisation, simplification, conceptualisation and/or description of a problem solving task in order to provide research-based insights for teaching. In order to reach this goal it is not sufficient to analyse manifest representations, written in acceptable scientific language (Greca & Moreira, 2000). Therefore, this study aims to describe the internal implicit representations (mental models) that are inferred from students' actions and the symbolic languages used (Vergnaud, 1991) during the process of constructing a model.

Pathways of Students' Conceptualisation of a Problem Solving Task

Conceptualisation (Lopes, Costa, Weil-Barais, & Dumas-Carré, 1999; Lopes & Costa 2007) involves attributing certain traits to objects and characterising the relevant events through a set of descriptors. Doing this allows the adoption of a global approach, guiding the subject's actions during the problem solving process. Conceptualisation has four characteristics: (a) it is not a facsimile copy of an epistemic object (Damásio, 2000; Vergnaud, 1994) but it is homomorphic; (b) it is dependent on the knowledge which is available regarding the subject, as well as its structure; (c) it is appropriate for problem solving (Marques, 1997), and (d) it may change during the problem solving process. A recent study (Lopes & Costa, 2007) indicated the importance of conceptualisation in the modelling process. However, the process of using and constructing conceptual models is not yet clearly understood (Clement, 2000), in spite of its importance in conceptual understanding in science. Therefore, this research must "look at both content and process goals" (Clement, 2000). Recently, a study by Borges and Gilbert (1999) showed how subjects' mental models of electricity evolved as they acquired experience and conceptual knowledge of the subject. The study was performed with different subjects and consequently, from this study, it was not possible to establish what happened in terms of the mental models of the same subjects during a problem solving task. Lopes and Costa (2007) carried out a transversal study where several characteristics of the conceptualisation of subjects with different physical background were identified. However, this study, like the previous one, did not focus on the conceptualisation process.

We aim to study the construction of mental models as a conceptualisation process that can lead to conceptual learning based on conceptual models. Conceptual learning through modelling comprises: (a) integrating the problem solving task into a class of problems known to the student or creating a new class of problems (Vergnaud, 1991; Lemeignan & Weil-Barais, 1994); (b) clarifying assumptions, correcting ambiguities and incorporating acceptable scientific knowledge into the mental model in order to transform it into a conceptual model (Norman, 1983; Duit & Glynn, 1996; Kleer & Brown, 1983), and (c) structuring and extending the set of concepts and what can be done with them (Vergnaud, 1991; Lemeignan & Weil-Barais, 1994). There has been some discussion about the connection between mental model building and conceptual learning (e.g. Taylor et al., 2003). These authors discovered contradictory results regarding this connection, however, they recognised that the learners also then need to affirm what has become 'their' mental model by using it to resolve related problems that are new to them and then by defending their problem solving to their peers in interactive debate. Similar results were also found by other researchers (e.g. Greca & Moreira, 2000), emphasising that there is no simple and direct relationship between a conceptual model and a mental model, because the students did not have the necessary knowledge of the field to interpret them as conceptual models or often do not understand that a conceptual model is a simplified and idealized representation of phenomena or situations, without being told the actual phenomenon or situation. Consequently, this research must address the process of the transformation of a mental model when students solve a new problem and how teachers can help students in this process.

Research Questions

Taking into account the gaps identified above, this study will devote particular attention to the pathways of students' conceptualisation when they are trying to solve a problem, and the elements of this process that require the intervention of a teacher. In the context of this paper, the expression "pathways of students' conceptualisation" is used to refer to the temporal sequence that occurs when students attempt to conceptualise a problem solving task in any way.

In particular, we will try to answer the following research questions: (a) what are the salient characteristics of the pathways of students' conceptualisation when they are trying to solve a problem solving task? In particular, do they depend on the student's academic achievements? and (b) under what conditions can conceptualisation lead to conceptual learning? In particular, what are the issues regarding conceptualisation pathways that need a teacher's support in order to lead to conceptual learning?

Methodology of Research

General Description of the Study and the Participants

In order to study the research questions presented above, the hammer task, as a context-rich problem (Heller, Keith, & Anderson, 1992), was chosen for students to solve in a normal classroom.

Hammer task (based on Walker (1975))

Physical situation:

John is sitting on a chair with a plank on his right leg, which he can change to other planks of different thickness, although all are of the same width and length. His friend Mario can use a hammer to hit the planks "normally" or karate-style. In order to study this situation we suggest that you, rather than hammering the plank on the leg, hammer on the plank(s) on top of an electronic scale. Like this, the force exerted on the electronic scale can be measured. Hammering is substituted by the fall of an object at a fixed height of 15 cm.

Experimental demonstration: the teacher execute the experience using: several planks with similar masses and bases with the same area which can be overlapped, an electronic scale, three balls with equal mass (one made of plasticine, one of glass, and the other one made of lead), a measuring tape, and a device to drop the objects.

Problem:

In order to interpret, understand and describe the physical situation **establish a relationship** between the force measured on the electronic scale and other quantities, in accordance with the conditions under which the hammering takes place. Express the required relation as precisely as possible.

The students worked in four groups. Each group was heterogeneous in terms of the students' results at school. On the other hand, all of the groups, between them, were heterogeneous. Therefore, it should be possible to create conditions under which it would be feasible to improve the students' interaction and facilitate the "thinking together" effect (Mercer, 2000). Using groups who obtained different results at school, it is possible to study the importance of academic levels in terms of the pathways of students' conceptualisation.

The problem solving process took six lessons (50 minutes each), spread out over a two month period. The class included 15 students (all aged 17), all studying physics. The teacher divided the class into four groups, with the purpose of solving the hammer task: these groups were A, B, C and D. The students were spread out according to their results in physics up until that point, as follows: group A comprised two students who were type G* and two students who were type M, group B comprised one type G student and two type M students, and groups C and D were made up of two type M and two type P students in each group. The topic of collisions had already been approached in the class by the teacher and several exercises on the subject had already been solved by all of the students.

The hammer task involved a physical situation in which a hammer hits planks of variable mass. The problem to be solved involved discerning the functional relationship between the force exerted on the planks and the force exerted on the object under the planks.

The structuring of the student's activities while they solved the hammer task was done through a sequence of subtasks (Table 1) and guidance tools (e.g. an object-interaction diagram (a diagram representing all of the pertinent objects and interactions in the relevant physical situation) and a cartoon of the situation in order to help to identify the main phases and instants (Dumas-Carré & Goffard, 1997), and a systems interaction diagram (similar to the object-interaction-diagram) (Lopes, 2004)).

Table 1. Sequence of salient aspects of the modelling process.

Presentation of the task	**Student homework:** To read the task and to try to understand the problem to be solved.
	Teacher discussion with class: Discuss the task in order to guarantee that the students have appropriated the problem. Discuss the role of experimentation and previsions in the problem solving process. Teacher executes experimental demonstration more than once. Students observe and ask the teacher questions.
Subtask 1	To draw a cartoon in order to identify the main phases and instants in temporal evolution of events. To make an object-interaction diagram and identify the relevant systems in the interaction diagram.
Subtask 2	To identify variables. To choose appropriate concepts to the problem's resolution. To build a functional relationship which will be tested.
Subtask 3	To identify the physical data and the number of values to be obtained in an experimental way in order to test the functional relationship.
Subtask 4	To analyse a table of experimental data without treatment and to construct a graphic functional relationship from the table.
	First dialogic synthesis (Scott, Mortimer, & Aguiar, 2006). Teacher discusses with students and helps them to structure and enrich their conceptual model of collision, extending it to situations which have not been dealt with up until that point, and taking into account the students' ideas and difficulties. The students identify the pertinent systems and sub-systems in other tasks.
Subtask 5	To build a theoretical mathematical expression in order to solve the problem. To compare the two functional relationships (one obtained theoretically, the other obtained from experimental results).
	Second dialogic synthesis. Teacher discusses the main aspects of the solving process which the students have already been through. Teacher also discusses the role of the variables and parameters in the functional relationship.
Final subtask	To analyse the new model and extend it to other similar situations.

The teacher helped the students only when strictly necessary, or when the students were not making any progress. Under these conditions, the teacher helped the students with their difficulties by asking questions and clarifying ideas but avoided giving any particular indications in terms of how to solve the problem.

This study consisted of: (a) the students' productions; (b) a transcription of the dialogues between the students within each group and between each group and the teacher; (c) a transcription of the teacher's interventions in the class during the execution of the task; (d) tasks and subtasks which were given to the students; and (e) the final model produced by each group of students.

Data Analysis

In order to analyse the pathways of the students' conceptualisation in facing and solving a problem, three categories have been proposed (see Lopes & Costa, 2007): (a) conceptualisation of the objects; (b) conceptualisation of the events, and (c) global characteristics of conceptualisation. The first two categories are directly based on the framework presented above. The third category is an open coding category, also based on the framework which has been previously presented.

Conceptualisation of objects. The students attribute, explicitly or implicitly, traits and/or physical variables or parameters to the objects of the physical situation that may be relevant to solving the problem. The objects represented may be a part or all of the objects that are relevant to the problem solving task.

Conceptualisation of events. The students attribute, explicitly or implicitly, a set of descriptors or physical relationships to the event during the temporal evolution of the physical situation of the problem. The events that are represented may be a part or all of the events that are relevant to the problem.

Global characteristics of conceptualisation. This involves evaluating whether the conceptualisations of objects and events are coherent and whether they are suited to solving the problem, and identifying any global characteristics of the conceptualisation.

In order to examine the pathways of students' conceptualisation, the analysis was performed in four steps:

First step: To select the areas of the study that are relevant to each student group's conceptualisation pathway;

Second step: To divide each part identified in the first step into units of analysis. Each unit was changed when there was a change in the conceptual aspects involved in the students' activity;

Third step: To analyse each unit of analysis with the pre-defined categories and the open coding category. The existence, or lack thereof, of conceptualisation of the objects or events involved in the problem and the global characteristics of the conceptualisation of the problem solving task were analysed;

Four step: To construct the pathway of the students' conceptualisation for each group. A group was considered to have a new attempt in their pathway of conceptualisation when: (a) a new set of conceptualisations of objects and/or events occurred; and/or (b) a new global characteristic of the conceptualisation appeared. For each group, the pathways of the students' conceptualisation were composed of the sequence of attempts to conceptualise the problem.

These four steps were carried out independently by two researchers and then verified by the research team. Initially, there were about 90% of accords. The remainder of disaccords were resolved after a discussion between the research team.

Conceptual learning. In order to examine conceptual learning, the quality of the final model produced by each group of students was analysed. Three criteria were used in order to characterise the quality of the final model: the conceptualisation of the problem, the explanations and predictions produced using the model, and the possibility of the extension of the model to other situations.This analysis was also carried out independently by two researchers and then verified by the research team. Initially, there were about 92% of accords. The remainder of disaccords were resolved after a discussion between the research team.

Results of the Research

The results in this section are organised around the two research questions.

Pathways of Students' Conceptualisation

Global Conceptualisation and its Characteristics

Using the open coding category "global characteristics of conceptualisation", the analysis of the students' models and the transcriptions of the dialogues between the students within each group and between each group and the teacher led to an emergent category that we have called "global conceptualisation" (GC). The characteristics of this category were identified from the data analysis. GC exists when a clear formulation of the direction of students' thoughts and actions helps in conceptualising the problem as a whole in a certain phase of the problem solving process, and mobilises the students in solving the problem, even if the solution is inadequate. Excerpt 1 illustrates the students' mobilizing idea of the problem solving task, viewing it as a whole, at the beginning of the problem solving process. In this excerpt, the students mobilised their attention towards a pertinent aspect of the experience. The students were convinced that their comprehension of the problem was good, judging by their smiles.

Excerpt 1 (group B)

Dialogue	Students' production
…Teacher: What is the problem? Student E: Study the force exerted on electronic scale… the relations between the forces and… for example, if I hammer on a plank over my leg will it hurt more with 1, 2 or 3 planks? [Smiles]	This group of students observed the experiment conducted by the teacher and asked her to repeat it successively with 1, 2 or 3 planks.

The same group of students tried to quantitatively relate the force to the kinetic energy of the fall based on the data available. This was a mobilising conceptualisation, which allowed the students to carry out their modelling work. However, as can be seen in the following excerpt, the students were able to conclude by themselves that their conceptualisation was wrong, that is, the students' GC allowed them to evaluate their actions and thoughts (see the final part of Excerpt 2). This excerpt clearly indicates that GC is refutable by the students themselves.

Excerpt 2 (Group B)

Dialogue	Students' production
Student E: How do you relate [kinetic energy] with the force? Student A: You know that F = m.a… will have the velocity … of course you already have gravity, you have the height of 15 cm… just lacks the velocity… Student F: We know that the acceleration is equal to v2… that centripetal acceleration is v2/r or v2/h… so we have acceleration… Student E: No… because we have no centripetal acceleration… [smiles] Student A: This destroys everything…	$E_i = E_f$ $m.g.hi + ½.m.v_i^2 = m.g.h_f + ½.m.v_f^2$ $m.g.h_i = ½.m.v_f^2$ ($v_i = 0$ and $h_f = 0$) $F \uparrow \leftrightarrow \uparrow E_k$

In conclusion, these two excerpts demonstrate the following characteristics of GC: i) the students view the problem as a whole, and this is significant as it allows the students to start solving the problem.

That is, they have a mobilising idea which consists of some kind of representation of the situation as whole, which allows the students to think and operate with the range of aspects that they recognise in the situation; ii) the mobilising idea allows the students to evaluate their own conceptualisation during the problem solving process; iii) the students are convinced, at a certain time, that their own conceptualisation can lead them to the problem's solution. Between the first and the second excerpt, the GC becomes supported by an external representation and therefore becomes more refutable.

In the instances when the first characteristic feature of GC (the mobilising idea) did not occur, the other characteristics subsequently did not occur, even though the conceptualisation was itself refutable. As can be verified in Excerpt 3, the idea is refutable but does not assume that a mobilising idea is present for students, because their concern is to find a mathematical expression and not to solve the problem. In addition, in this excerpt, the students' idea is fragmented and does not mobilise any action: there are several long pauses containing neither work nor dialogue.

Excerpt 3 (group C)

Dialogue	**Students' production**
Student D: Following the Newton law to relate the force with the speed that can only be made through the acceleration… [Pause]	$\textcircled{F}$= m.a $\textcircled{v}$
Student M: There is another one, isn't there? [another Mathematical expression]…	
Student D: There is! This is our formula … calculating this… [Pause]	$v^2 = v_0^2 + 2.a.\Delta s$
Student A: the systems are the ball and the other the electronic scale. [pause]	$v^2 = \cancel{v_0^2} + 2.a.\Delta s$
Student Ab: What interests us is the force… we can go for this [formula]… this here… but I don't know if we can go with this…	$v^2 = 2.a.\Delta s$ $a = v^2/[2.\Delta s]$
[long pause, about 6 minutes].	$F = m.\ v^2/\ [2.\Delta s]$

In fact, in Excerpt 3, there are none of the main characteristics of GC: a) the problem is not viewed as a whole with significance; b) the students do not evaluate their conceptualisation; c) the students are not convinced that their own conceptualisation will lead them to the solution to the problem.

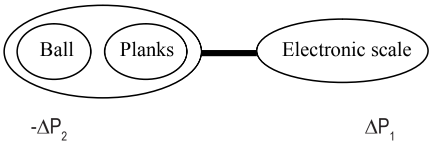
Description of the Conceptualisation Pathways

The conceptualisation pathway was identified for each group according to the criteria indicated in the data analysis section. The identification of GC in each pathway of the students' conceptualisations used the characteristics presented in the previous section. More details of group B's modelling process will be presented, because this was the group with the greatest variety of conceptualisations.

Description of the conceptualisation pathways of group B

When group B analysed the hammer task, they made the first attempt to conceptualise the problem: it was a GC (Table 2, first attempt) of the problem, even if it was inadequate (see Excerpt 1). There was no conceptualisation of objects or events. After this, group B analysed the events of the hammer task and had a second attempt at conceptualising the problem (Table 2, second attempt). The students focussed their attention on aspects such as the impact of glass on the plank, the elastic collision, the impact of plasticine on the plank and the non-elastic collision. Events including the fall, the impact and the rebound were conceptualised. However, there was no mobilising conceptualisation that allowed the students to search for a solution. In the third attempt at conceptualisation, the students focussed on their GC of the hammer task and on the conceptualisation of its objects and events. The pertinent systems of the problem were identified and the students also tried to relate the relevant concepts to mathematical expressions by searching for the relationship between force and energy. There was GC, but it remained inadequate. In the fourth attempt, the students tried to quantitatively relate the force with kinetic energy. There was a conceptualisation of the ball falling as an object point within gravity field. There was also a mobilising conceptualisation, which guided their approach to the problem and allowed the students to conclude that their conceptualisation was wrong. Therefore, the students had clearly achieved GC (Excerpt 2). When group B tried to analyse the experimental data regarding the situation (Table 2, fifth attempt), they did not advance to the point of GC. However, after the first dialogic synthesis, group B worked on the hammer task in an attempt to solve it. They explicitly tried to conceptualise the problem and attempted to become operational (Table 2, sixth attempt). The sixth attempt to conceptualise the hammer task led an adequate GC (see Excerpt 4): group B conceptualised the problem as needing to be solved using the relationship between force and the temporal variation of ΔP in the pertinent system.

Excerpt 4 (group B)

Dialogue	**Production**
Student E: The variation of P is final P minus initial P … there is conservation… this was an isolated system… Student A: Why do we need to know if the speed and mass of the plank is quiet? Student E: The ball falls on the plank knocking it down. Student A: The plank? Student F: Having the electronic scale under plank? Student E: Down, down!	 $\Delta P = P_f - P_i$ $\Delta P = P_f - P_i = (-m_b.\sqrt{(2.g.h_r)} + m_P.v_P) - m_b.\sqrt{(2.g.h_i)} =$ $-m_b.\sqrt{(2.g)}.[\sqrt{(h_r)} + \sqrt{(h_r)}] + m_P.v_P$ After the teacher helped him, the student wrote: $F \propto \Delta P' = -\Delta P = m_b.\sqrt{(2.g)}.[\sqrt{(h_r)} + \sqrt{(h_r)}] - m_P.v_P$

The following was an attempt to characterise the model and expand it in order to make it relevant to other situations (Table 2, seventh attempt). As can be seen above, group B did not distinguish between variables and parameters. Therefore, the teacher needed to make a dialogic intervention with regards to that issue. It was only in the seventh attempt that the model became explicit and was completed. This conceptualisation helped to identify the relevant systems in the interaction and the mass of the interposed object as relevant physical data. When the task asked the students to imagine other situations in which the use of the same physical model would be possible, group B described a pertinent situation. Only on the sixth attempt did their GC become a conceptual model, and it only became explicit and operational on the seventh attempt.

Table 2. The conceptualisation pathways of group B.

Stage of work	Brief description of conceptual activity in terms of representing the hammer task (in attempts)	Type of conceptualisation present								
		Events			Objects			Global		
		Rebound	Fall	Collision	Planks	Scale	Ball	Inadequate	Adequate	Complete
Subtask 1	1st attempt: The extent of the force exerted on the electronic scale depends on the type of balls and the number of planks used.							X		
	2nd attempt: The main events were identified: fall, rebound and collision (qualifying the collision as elastic for the impact of the glass ball and non-elastic for the impact of the plasticine). The temporal separation of each event was also completed.	X	X	X						
	3rd attempt: The problem was analysed in terms of events (fall, collision and rebound) and the relevant objects (electronic scale, ball, planks), and interactions between the objects were identified. The group identified the systems in terms of interactions: scale and ball + planks.	X	X	X	X	X	X	X		
Subtask 2	4th attempt: The group tried to associate force with the ball's kinetic energy. The idea was explored and it was concluded that it was not valid. The relationship between the speed of the ball and its initial potential energy remained.		X	X	X	X	X	X		
Subtasks 3/4	5th attempt: It was identified from experimental data that the force varied according to the type of collision involved (this depended on the height of the rebound) and on the height and mass of the planks.	X	X	X						
	First dialogic synthesis with students									
Subtask 5	6th attempt: The group identified the interaction between the electronic scale system and the ball-planks system; P was conserved in the ball-planks-electronic scale system; the force exerted on the electronic scale was proportional to the variation of P in the ball-planks system; the height from which the ball fell (rebound) determined its initial speed (final); the linear moment of the plank was not nil.	X	X	X	X	X	X	X		
	Second dialogic synthesis with students									
Final sub-task	7th attempt: This included the same aspects as the sixth attempt as well as the following: (a) the force exerted on the plank was greater than the force exerted on the electronic scale (operational relation); (b) in another context, the vital step would be to identify the systems in interaction; and (c) the plank was an interposed object, and its mass was the relevant physical data.	X	X	X	X	X	X		X	

Description of the conceptualisation pathways of the four groups

The conceptualisation pathways of group A were similar to those of group B (see Table 3). The main differences were that a GC appeared later (subtask 2), and that in the final subtask the GC was not complete.

In groups C and D (Table 3) conceptualisation practically only existed when it was explicitly requested. A GC did not occur for group C. Group D formed inadequate GCs in subtask 5 and the final subtask.

Table 3. Synthesis of the conceptualisation pathways of groups A, B, C and D.

Stage of work	Type of conceptualisation present								
	Events			Objects			Global		
	Rebound	Fall	Collision	Planks	Scale	Ball	Inadequate	Adequate	Complete
Subtask 1							╬		
	▌╬▲☼	▌╬▲☼	▌╬☼	☼		☼			
	▌╬	▌╬	╬	╬	╬	╬	╬		
Subtask 2		╬▲☼	▌╬	╬	╬	▌╬	▌╬		
Subtask 3/4	╬	╬☼	▌╬	▌☼		▌☼			
First dialogic synthesis with students									
Subtask 5	▌╬▲☼	▌╬▲☼	▌╬	▌╬☼	▌╬	▌╬▲☼	☼	▌╬	
Second dialogic synthesis with students									
Final subtask	▌╬▲	▌╬▲	▌╬☼	▌╬▲	▌╬▲☼	▌╬▲☼	☼	▌	╬

▌, ╬, ▲ or ☼ indicates the presence of conceptualisation in groups A, B, C or D respectively. The number of lines for each group indicates the number of attempts: six for group A, seven for group B, four for group C and five for group D

Analysis of the Quality of the Final Models

The characteristics found in the students' work following the final subtasks for each group are presented in Table 4. The order of the quality of the final models produced by each group, in terms of the best to the worst, were B, A, D and then C. The models of groups A and B were very sophisticated. However, these groups did not consider all the consequences, particularly in terms of their previsions. The data on the extension of the model (Table 4) gave us indicators of the students' conceptual learning through the modelling process. The conceptual learning process was consistent for groups A and B and autonomous for group B. There are no indicators of the conceptual learning involved in the modelling process for groups C and D. Taking into account the quality of the final models and comparing these models with the characteristics of each group's conceptualisations, it can be argued that the students' conceptualisation of the problem clearly affected the quality of their final models and their conceptual learning.

Table 4. Characteristics found in the each group's work during the final subtasks.

Characteristics		Groups			
		A	B	C	D
Model quality (conceptualisation, explanations and predictions)	The situation was conceived as a collision between system S1 (the electronic scale) and system S2 (ball + planks)	P	P	-	-
	They derived the functional relationship of force	P	P	P	P
	They considered that the force exerted on the electronic scale was related to the force exerted on the planks	P	P	-	-
	The force exerted on the electronic scale was well explained	-	P	-	-
	Some previsions were made according to the model	P	P	-	P
Conceptual learning (extension of the model)	The model was used in the proposed situation	P	P	-	-
	Other situations were chosen where the use of the model was possible	-	P	-	-

"P", means that a characteristic is present; "-" means that a characteristic is absent

Salient characteristics of the pathways of the students' conceptualisation

Each group had its own conceptualisation pathway. However, comparing the various conceptualisation pathways (Tables 3 and 4) allows us to identify some salient characteristics of the pathways of students' conceptualisation:

1. In general, the conceptualisation of events precedes the conceptualisation of objects (groups A, B and C). This may be more relevant when the conceptualisation of objects is more difficult as they have an usual function, as is the case in the hammer task.
2. When there is any type of GC, all objects and events are considered for conceptualisation (group A, fifth and sixth attempts; group B, third, sixth and seventh attempts). However: (a) GC can exist in cases where some objects or events are not conceptualised (group A, third attempt; group B, first and fourth attempts; group D, fourth and fifth attempts), and (b) if the GC is adequate, all objects and events are conceptualised (group A, fifth and sixth attempts; group B, sixth and seventh attempts).
3. In general, it is necessary condition having a conceptualisation of the collision for have any type of GC (group A, third, fifth and sixth attempts; group B, third, fourth, sixth and seventh attempts; group D, fourth and fifth attempts). That is, the conceptualisation of one event is crucial for the existence of any type of GC.
4. The conceptualisation pathway is influenced by the sequence of proposed subtasks. In fact, in general, there were new attempts at conceptualisations only when a new subtask was proposed. However: (a) There were some subtasks (subtasks 3 and 4) that did not excite any type of GC in any of the groups or any type of conceptualisation, for that matter (group C), that is, some subtasks may not have been well formulated, or the students may have had particular difficulties with this particular kind of work, and (b) there was one subtask (subtask 1) that elicited more than one attempt at conceptualisation (groups A and B), that is, some tasks, either by their formulation, or due to guidance tools, stimulate conceptualisation.
5. Each conceptualisation attempt has its own pattern. In particular: (a) Some conceptualisations of events or of objects may be not have been taken into account in the subsequent attempts (all groups), and (b) the conceptualisations of events or of objects are taken into account in subsequent attempts if there is an adequate GC (group A, fifth and sixth attempts;

group B, sixth and seventh attempts) so it is not enough to have any type of GC (group D, fourth and fifth attempts).

6. Conversations with the teacher were very important for all the groups, as they increased the number of conceptualisations (from conceptualisations in subtasks 3 and 4 to conceptualisation in subtask 5), the likelihood that a GC would form (group D), and improved quality of GCs (groups A and B). However, conversations with the teacher were only effective (through helping the student to form an adequate GC and conceptualise all relevant objects and events) if there was previously some kind of GC (groups A and B). This effect was greater in group B, as they had formed more GCs before the dialogic synthesis (conversation). The main difficulties were conceiving of the situation as a unique interaction between systems, and consequently considering the exchange of a linear moment between systems.
7. There was a significant relationship between the number of GCs and the number of conceptualisations of events and objects in each group (Figure 1). This relationship emphasises the importance of the GC in conceptualising a problem. That is, the activity of conceptualisation increases drastically when attempts to perform a GC increase. Without any kind of GC, there is a minimum of conceptualisation activity. In particular: (a) GC seems to play an important role in the conceptualisation pathway since it may occur prior to any specific analysis of the problem (see group B, first attempt) and can occur without a complete conceptualisation of all of the relevant objects and events (see group A, third attempt and group B, first, third and fourth attempts), (b) the quality of GC increases with consistent external representation (groups A and B), and there is a moment at which it becomes a conceptual model since when this occurs, the students are able solve the problem and later extend their model to other problems, and (c) the groups that searched for a GC from the beginning of the problem solving process then evaluated this process (see, for example, group B: systematically worked towards a GC) since it seems that this guided the problem solving process by facilitating the conceptualisation of objects and events (see also 5.).

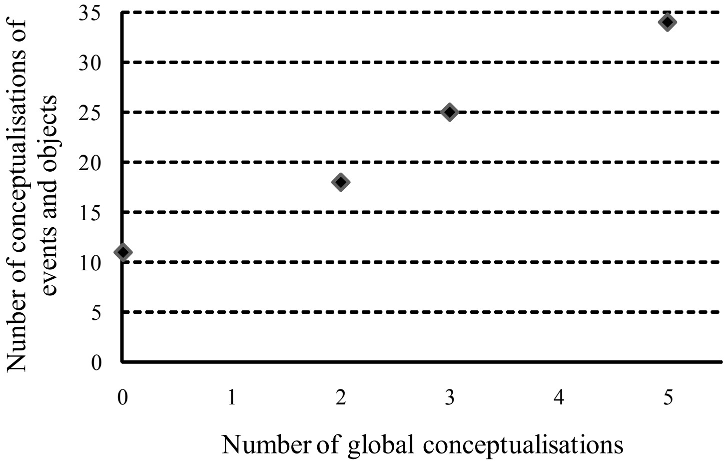


Figure 1: **Number of GCs versus the number of conceptualisations of events and objects for each group (Pearson's correlation, r = 0.993, significant at p<0.01).**

Conditions Under Which Conceptualisation Can Foster Conceptual Learning

The data regarding the final model (especially its potential extensions) produced by each group (Table 4) and the data concerning their conceptualisation pathways allows us to state that conceptual learning was made possible through modelling. However, it was necessary to perform explicit work on the extension of the model (with the teacher's help) and personal work on conceptualisation, especially GC.

The hierarchy of the student's previous results was, as referred to above: first - group A, second - group B, third - groups C and D. On the other hand, the levels of conceptualisation were: first – group B (five GCs and 34 conceptualisations of objects and events), second – group A (three/25), third – group D (two/18) and fourth – group C (zero/11). These results show that school results are not sufficient to facilitate the generation of conceptualisations by the students. These results also show that prior knowledge is a necessary condition, but not sufficient, for the adequate representation of a problem. The comparison of groups A and B with groups C and D indicates the need for a structured and expansive conceptual model of collisions in order to produce a satisfactory solution. The comparison between groups A and B indicates that it is not sufficient to be able to extend the model to other situations. The quality of the model and its potential usage in other situations (Table 4) is related to the quality and number of conceptualisation attempts. If students' academic results are, in any way, an indicator of the structure and extension of the conceptual models they will produce, then our results corroborate the hypothesis that global conceptualisation is a skill that involves using a conceptual model in a flexible way.

The data analysis allowed us to identify three conditions under which conceptualisation can foster conceptual learning:

i. The systematic search for a GC can foster conceptual learning;
ii. The existence of subtasks and guidance tools fosters conceptual learning;
iii. The existence of a dialogic synthesis between the student's work and knowledge fosters conceptual learning.

In summary, the groups that searched for a GC from the beginning of the problem solving process had a more explicit and operational final model as well as having a richer and more operational extension of the model for use with other problems. For example, group A, who made less use of GCs, was not able to imagine a new situation in which the use of their physical model would be possible. Therefore, the data supports the main conclusion of this section: the conceptualisation of a problematic situation can promote conceptual learning, and this is related with the systematic search for a GC.

The student's activities were supported through subtasks and guidance tools. The sequence of subtasks formed the structure of the students' activities. In fact, as can be seen above, in the majority of cases, the groups only made a fresh attempt to conceptualise the problem when the subtask was changed. The representational guidance tools which were proposed (see Table 1) were used by all the groups, and some of them appropriated them: for example, group B used the systems interaction diagram, as proposed in subtask 1, in subtask 5 (see Excerpt 4).

Each dialogic synthesis (see Table 1) was conducted after a careful examination of the students' products and dialogues aimed at identifying the type and the nature of their difficulties. In this analysis, the teacher and the researcher identified the students' sets of concepts of collision in terms of their structure, extension, relationships and operational use in problem solving tasks. The former was characterised by a long dialogue, in which the teacher tried to structure the use of the main concepts of force, energy, linear momentum, system, and collision in different situations without using technical details. This dialogic synthesis achieved four important objectives: i) it clarified the relationship between the concepts; ii) it extended the range of situations where the conceptual model of collision could potentially be used; iii) it structured the conceptual model of collision, and iv) it clarified the use of the conceptual model of collision in different situations. As the results regarding the students' pathways of conceptualisation suggested, this dialogic synthesis facilitated the elaboration of their conceptual models of the problem. However, its influence was different for different groups: it was greater for the groups who systematically used GC. The second dialogic synthesis was characterised by the clarification of the statute of variables and parameters in the physical model of the hammer task. In both dialogic syntheses, the teacher helped the students to work with their conceptual models.

Discussion

Our results confirm several well known results of problem solving research, namely: i) the erratic component within each conceptualisation pathway is related to the need for a solution to the problem that guides the students to make several attempts at conceptualisations (Dumas-Carré et al., 1992); ii) the structure and extent of a conceptual model is not static and may be improved in order to solve new problems (Vergnaud, 1991), and iii) the quality of a representation is closely linked with the available knowledge and with the way in which it is organised (Johsua & Dupin, 1993).

As the teacher's role in the students' conceptualisation pathways was to intervene only when the students could not, by themselves, advance in their solution of the problem, it was possible to identify the salient characteristics of the conceptualisation pathways in which the teacher could have a determinant role and the conditions for their effectiveness. Therefore, the results indicate new opportunities for teaching problem solving, as we will now discuss.

There is one type of conceptualisation (GC) that is different from the most common kinds of conceptualisation (the conceptualisation of objects and events) and influences, in a certain way, the pathway of students' conceptualisations. The results indicate three characteristics of GC: i) the existence of a mobilising idea that includes an overview of the problem, avoiding gross errors (Ikonicoff, 1999) and allowing the students to operate within the problem; ii) allowing the students to systematically evaluate their work; and iii) that the students are convinced that their GC can lead them to the solution to the problem. The GC becomes more operative if it is supported by an external representation.

These results support the concept that a GC can precede any analysis of a problem, or a complete conceptualisation. This result is in line with the results obtained by an investigation into mathematical reasoning (Ikonicoff, 1999). In addition, these results support the idea that students who systematically try to design a GC: i) improve their conceptualisation pathways; ii) obtain more conceptualisations; iii) consider their own previous conceptualisations, and iv) better appreciate the teacher's help. Therefore the students can obtain a better final model and improve their conceptual learning, since they can extend their model to new situations. These results indicate that one condition for problem solving improving conceptual understanding, as suggested by Gaigher et al. (2007), is trying, systematically, to achieve a GC of the problem. This can be aided by a teacher because the students can initially design a GC without a deep understanding of the problem. The results suggest that whether or not the teacher can help students understand the main events to be conceptualised and their roles, the students may develop the skill of being able to use their conceptual models in a flexible way, building GCs *ad initio* while attempting to solve the problem.

These results show that if a student's knowledge is not well structured (regarding the problem to be solved) the physical situation of the problem to be solved appears as an obstacle in the extension of their conceptualisation, according to the findings of Hung and Jonassen (2006). These results also show that the students who had better GCs (not necessarily the ones with better prior knowledge) underwent a deeper process of conceptual learning; they used the model of the problem as a conceptual model. Therefore, the relationship between problem solving and conceptual understanding is not simple. The fact that some students with poorer academic results created more complete GCs supports the hypothesis that conceptualisation is a skill which entails the flexible use of a conceptual model in accordance with the physical situation. This skill is one way of articulating the elements of a conceptual model, which is necessary in order to approach and solve a problem. The role of a GC appears to be crucial for understanding the way in which someone mobilises his or her conceptual model when confronted by a physical situation in order to solve a problem. GC may be able to create the conditions for the students enrich and structure their conceptual models, with the teacher's help. As these results have shown, the conceptualisation pathway improved (more conceptualisations, consideration of previous conceptualisations and raising or improving the GC) when there was a greater level of intervention from the teacher (through dialogic synthesis), or when the subtask gave the students some control over what they could do (Lopes et al., 2008); in this case, this occurred through the use of guidance tools (e.g. object interaction diagrams). Therefore, conceptual understanding facilitates problem solving if the teacher can help the students to restructure their own conceptual field through appropriated dialogic synthesis and/or giving students sufficient control over their work.

One the other hand, it is important to find a solution to a problem and be able to extend it to other situations because conceptual learning is not the construction of a particular model but the elaboration of a conceptual model in order to face a range of problems (Walliser, 1977). An appropriate conceptual understanding is a necessary condition for the formation of a suitable GC, but it is not enough; in addition, persistent attempts to form a GC facilitate conceptual learning. The confluence of the students' efforts (systematic attempts to form a GC), alongside the teacher's efforts (e.g. dialogic synthesis and/or giving the student control over their own work, namely through the task design), as the results showed, are very important for student success. In spite of the limitations of this study (e.g. the role of the teacher was not investigated in any depth), the need for the systematic confluence of the efforts of the students and the teacher has emerged as a clear direction for future research.

These results support the concept that external representations associated with a GC may become themselves the objects of reasoning (Vergnaud, 1991), and thus contribute to the adjustment and enrichment of conceptualisation itself, as well as, of course, the quality of the final models. In particular, the GC is generally richer if it integrates external representations.

Conclusions and Implications

As expected, the study has confirmed, once again, certain concepts regarding the modelling process in a problem solving task. Nevertheless, it has also provided new insights into teachers' roles in students' conceptualisation pathways. As GC plays an important role in the pathway of students' conceptualisation, students require some kind of GC in order to: i) form more conceptualisations; ii) fully understand the teacher's help; iii) take into account previous conceptualisations, and iv) consider all relevant objects and events.

The teacher has two fundamental roles in students' conceptualisation pathways: i) in task design, and ii) in teacher mediation.

In task design it should be checked whether the subtasks may induce the conceptualisation activity, in particular if they may give students control over their own work.

In teacher mediation, any interventions by the teacher, when students are trying to solve a problem solving task, should focus on:

- The student's efforts to conceptualise the central event of the problem;
- The student efforts to form a general picture of the solution in order to construct an adequate GC. The focus here is to discern whether the students have formed a GC, by searching for the answers to these questions: are the students convinced about the potential of their idea? Can the students evaluate the progress of their work using their mobilising idea? Any assistance should take this direction: from the conceptualisation of the central event to the remaining relevant events and from the conceptualisation of events to the conceptualisation of objects, which is always supported by any type of GC. The students' prior knowledge is a necessary condition for this purpose, but not sufficient to ensure it;
- Dialogic synthesis of several conceptualisations, taking into account the students' conceptual field.

Through synthesis, the teacher can improve the students' approach to a problem if he/she encourages the students to form a global approach to the problem before any specific analysis occurs, even if, at first, the approach is not clear and precise. The teacher can help the students to elaborate on their GC by encouraging them to be flexible and creative in using the conceptual model according to the physical situation.

Note

* A student is "type G" if his/her school results (SR) in physics are SR>14 on a scale from 0 to 20, "type M" if his/her SR in physics are 10≤SR≤14 and "type P" if SR<10.

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Received: *April 10, 2010* Accepted: *January 30, 2011*

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