CHEMICAL CONCEPTS IN MOTION: THE ROLE OF COLLECTIVE SCHEMES ON THE LEARNING ABOUT INTERMOLECULAR INTERACTIONS

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Abstract

The purpose of this research is to access data related to how College students collectively develop structural schemes during the resolution of experimental problems of investigative nature. This research included two situations presented to six students in the Undergraduate and Teacher's Licensure Chemistry Course at the Federal University of ABC (Brazil) involving Liquid Chromatography contents. The students were divided into groups and asked to make a decision about the best experimental conditions to separate a mixture of chlorophyll, xanthophyll and b-carotene in spinach extract. They possessed different stationary phases and elements. The students' explanations were recorded on an audio-visual device and analysed via computer assisted qualitative data analysis software *(CAQDAS) supported by the Transana software. As a result, evidence of the collective development of a scheme characterized by conceptual relations pertinent to the structural field was identified; however, such evidence was incomplete. The interference of the teacher in the students' decision making was a relevant factor during the resolution of the problems. Conceptual and logical operations of thinking (operative invariants) gaps may be an opportunity for a pedagogical intervention during the resolution of problems in the classroom.*
Keywords: *Theory of Conceptual Fields, collective schemes, intermolecular interactions.*

Introduction

Different studies suggest the existence of alternative views about chemical bonds in High School and College students (Peterson & Treagust, 1989; Birk & Kurtz, 1999; Riboldi, Pliego & Odetti, 2004; Franco & Ruiz, 2006; Othman, Treagust & Chandrasegaram, 2007; Özmen, 2008, Özmen, Demircioğlu, & Gokhan, 2009; Fernandez & Marcondes (2006) performed a review of the main students' views about chemical bonds. The categories presented show explanations that are different from what the scientifically acceptable explanations would be: i) confusion between ionic and covalent bonds; ii) anthropomorphisms; iii) octet rule; iv) conceptual mistakes involving molecular geometry and polarity; v) confusion about bond enthalpy and vi) difficulties with bonding representation.

The understanding of the molecular and intermolecular phenomena associated with chemical transformations involves concepts about the nature of chemical bonding. Harrison and Treagust (1994) claim that in order to understand concepts related to the atomic molecular context, the students must be capable of noticing the flow between the observation and formulation of models. Working with explanatory models is a fundamental condition of the chemical knowledge and without them teaching would be only a simplistic description of macroscopic properties. However, since chemical bonding is an abstract topic, it allows the use of several models and theories for conceptualization, turning it into a complex topic and increasing the reinforcement of alternative views of the students (Fernandez & Marcondes, 2006). That being said, it is necessary to continue to investigate the learning process of this topic with the aim of improving learning in Chemistry Teaching.

To Vergnaud (2009), cognitive development is strongly influenced by the contents of teaching. The Theory of Conceptual Fields states that the fundamental point of the cognitive process is the conceptualization of what is real. The author also emphasizes that the psychological activity of the subject cannot be reduced to the general logical operations and exclusively linguistic operations.

In the Theory of Conceptual Fields, the formation of a concept is associated with the triad (*S*,*I*,*R*) (Moreira, 2002). In this proposition, *S* corresponds to situations that give meaning to the concepts, *I* corresponds to the operative invariants, which are responsible for the conceptual content and operability of the schemes, while *R* is the component related to verbal and non-verbal formats which allow a symbolic representation of the concept, its properties and treatment procedures. Considering this approach, the study of conceptual evolution throughout the learning process or even its use requires considerations about this triad.

The link between the subject and the situation requires courses of action guided by internal representations. It is noteworthy that the theoretical framework proposed by Vergnaud is based on the concept of a scheme as the way to make it operational. To Vergnaud, the schemes are accessible to the subject, acting as effective organizers of thinking and conscious actions.

Research Problem

Even though the difficulties reported in the conceptual scope are well known, it is still necessary to investigate how they advance and step back in classroom situations where there is interaction between the subjects. Thus, the purpose of this research is to access data about how a group of students is capable of contributing to the conceptual advance in the structural field during the problem solving in a sequence of experimental teaching involving the intermolecular interactions existing in a chromatographic separation.

The purpose of this research is to answer the following questions:

1. Which concepts and operative invariants do undergraduate students in situations (tasks) of an experimental nature involving intermolecular interactions (structural field) mobilize?
2. Which factors influence the mobilization of collective schemes by undergraduate students? Is the influence of the teacher fundamental in this process?

Methodology of Research

General Background of Research

The results of this research were obtained from the explanations given by students during a 12 hour chromatography course in a Brazilian university. The study was conducted qualitatively, seeking for conceptual contents and explicit and implicit operations in the explanations. As a working hypothesis, it was considered the assumption made by Marcel (2006) in which the speech of an individual in collective situations creates a collective psychic subject characterized by the contributions of the individual schemes. This research is a part of a broad study about how chemical concepts evolve over time on college students.

Participants and Setting

An experimental chromatography course was offered to the Bachelor in Science and Technology (BS&T) students of the Federal University of ABC – Brazil. The course discussed polarization and intermolecular interactions. The prerequisite to participate in the course was that the student had been approved in General Chemistry. The course was divided into three moments that discussed the theoretical aspects of several types of chromatographic separation and one experimental activity as investigative task. Six students participated in the activities. They were enrolled in an additional specific program to BS&T: Materials Engineering, Bachelor in Chemistry and Chemistry Teaching. A description of the participating is briefly presented in Table 1:

Table 1. General characterization of the experimental course.

Student	Bachelor in Science and Technology	Materials Engineering	Bachelor in Chemistry	Chemistry Teaching
A1	**X**			
A2	X			X
A3	X	X		
A4	X			
A5	X		X	
A6	X		X	

Instrument and Procedures

During the first day, the theoretical approach focused on chemical bonding, polarization, intermolecular interactions and fundamentals of liquid chromatography. Subsequently, having the students divided into pairs, a task based on the proposal of Johnston et al (2013) was presented. The purpose of this proposal was to empirically discover which is the appropriate mixture of elements to separate the main components of a spinach extract via chromatography. Two situations were presented, i) a chromatography column containing saccharose ($C_{12}H_{22}O_{11}$) as stationary phase; ii) containing silica (SiO_2) as stationary phase. The tests were performed by the students, who were looking for several solvent proportions to separate the components of spinach extract applied on plates of thin layer chromatography (TLC). Table 2 lists the cases presented to the students:

Table 2. Distribution of tasks between the participants.

Situation	Objective	Students
1 – Saccharose chromatographic column task.	To find the appropriate decane (commercial solvent) and ethyl acetate mixture to prepare an eluent to perform the chromatography of the spinach extract with saccharose ($C_{12}H_{22}O_{11}$) as stationary phase	Group 1: A1 and A2 Group 2: A3 and A4
2 - SiO_2 chromatographic column task.	To find the appropriate mixture of hexane and acetone to prepare an eluent to perform the chromatography of the spinach extract with SiO_2 as stationary phase	Group 3: A5 and A6

After deciding which the best proportion to prepare the eluent was, the students explained orally the reasons for their choices based on empirical results obtained from the TLC separations and based on the chemical structures of the main components of the spinach extract that were previously informed (chlorophyll, xanthophyll and b-carotene). At this point, it was expected that the students explained the different R_f obtained in the TLC based on polarity effects and the nature of the molecular interactions. The explanations were recorded on an audio-visual device, being the first data collection moment (M1). On the second day, the chromatographic column was prepared following the conditions studied in the previous day. The students evaluated the fractions obtained from the columns in TLC, then combined and analysed by a spectrophotometer in the visible spectrum.

Finally, the third day of the course was dedicated to the analysis of the electronic spectra with the aim of assessing the efficacy of the chromatographic separation on the chosen elution conditions. The students presented their results orally to the teacher and participants. The groups that used different stationary phases were encouraged to analyse their data together. Once again, it was expected that the explanations considered the nature of intermolecular interactions, the polarity effects on the different components of the eluent and the chemical structure of the stationary phases and solutes in order to evaluate the efficacy of the chromatographic strategy. This step was also recorded on an audio-visual device, being the second data collection moment (M2).

During M1 and M2 the teacher intervened in two complementary moves: the teams should explain *how* they proceeded, and *why*. The other teams also participated in the elaboration of the explanations by stimulating the discussion presenting data from their own experiments.

Data Analysis

The content of the oral explanations were transcribed and subjected to Discourse Textual Analysis (DTA) via CAQDAS, Computer-Assisted Qualitative Data Analysis Software (Galiazzi & Moraes, 2006) supported by the Transana software (Winconsin Center for Educational Research [WCER], 2011). DTA presumes the fragmentation of the text into manageable sub-groups called unities of meaning. In order to attribute meaning to the textual units, the criteria below were organized in dimensions (Table 3):

Table 3. The dimensions used in the data analysis.

Dimension	Definition	Indicator
Conceptual	Arise from the resolution of tasks and connect to the operative invariants and symbolic representations related to the structural field.	Aromaticity, steric effect, inductive effect, electronegativity, polar covalent bond, resonance and stereochemistry (Mullins, 2008; Nascimento & Bueno Filho, 2013)
Operative invariants	Concepts and implicit or explicit theorems used by a subject when facing a situation. They are often characterized by general logic operations of thinking.	Establishing relationships between the sub-microscopic model and the symbolic representation and simultaneity of events.
Explanations	Structure that characterizes the sequence of the student's actions.	Justifications and Conclusions

Results of Research

Characteristics of the Collective Schemes Developed by the Students

As previously highlighted, during the first day of activities the theoretical aspects of chemical bonding, intermolecular interactions and fundamentals of chromatography were discussed. Additionally, an investigative task was conducted to determine the elements used in the separation of spinach extract components on a silica or saccharose column; followed by an oral presentation (M1). The analysis of the justifications presented by the students A5 and A6 showed conceptual details about their decision making process when faced with the problem proposed on the experiment.

When the teacher asked these students to explain how they chose the appropriate proportions of hexane and acetone, they considered the importance of the concentration of one of the components of the solution on the polarity of the eluent. However, they did not highlight the possible relations between the eluent polarity and the intermolecular interactions existing between the substances in solution and the stationary phase of the TLC plate (SiO_2). This can be observed on the initial speech of A5, who reported higher elution of b-carotene when the eluent contained a higher proportion of hexane. It is observed that the chemical structures and intermolecular interactions were not mentioned.

A5: we started the test with a higher proportion of hexane than acetone and observed the beta-carotene was carried first, however, we could not identify... (0:00:29.9)

A5: there was an analyte spot and subsequently the group decreased hexane concentration and increased acetone concentration, and reaching 50:50 we observed better results...(0:00:46.1)

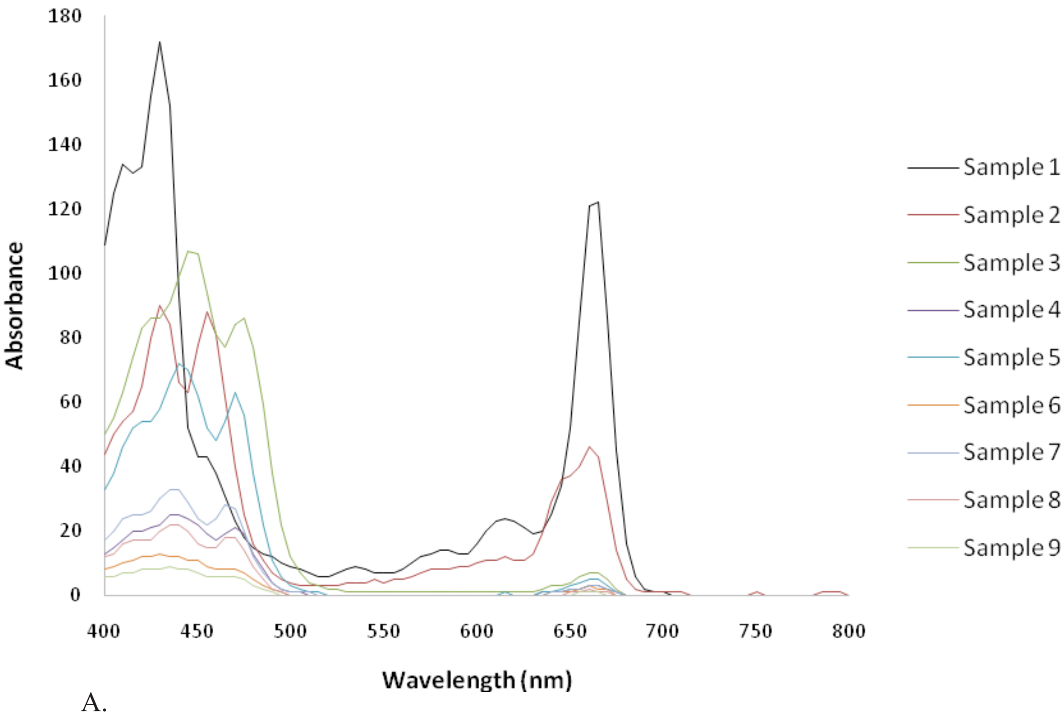
A6: in the end, we chose to use 50:50, increasing the polarity... (0:01:06.0)

To Johnstone (2000), the understanding of the chemical knowledge involves three different representation modes: the macroscopic, sub-microscopic and symbolic. The macroscopic mode involves every observable phenomena; on the sub-microscopic mode, a chemical phenomenon is represented by a spatial arrangement and by the movement and/or interaction of molecules, atoms, ions, electrons or other chemical species. The symbolic mode is related to the written part of the phenomenon and to the language used chemists, for example, symbolic representations of atoms, molecules, formulas, equations and structures. Regarding the difficulty to go from one mode to the other, Gillespie (1997) states the many students have difficulties with sub-microscopic and symbolic representations because they are abstract. Moreover, the students cannot establish appropriate relations between the macroscopic and sub-microscopic modes.

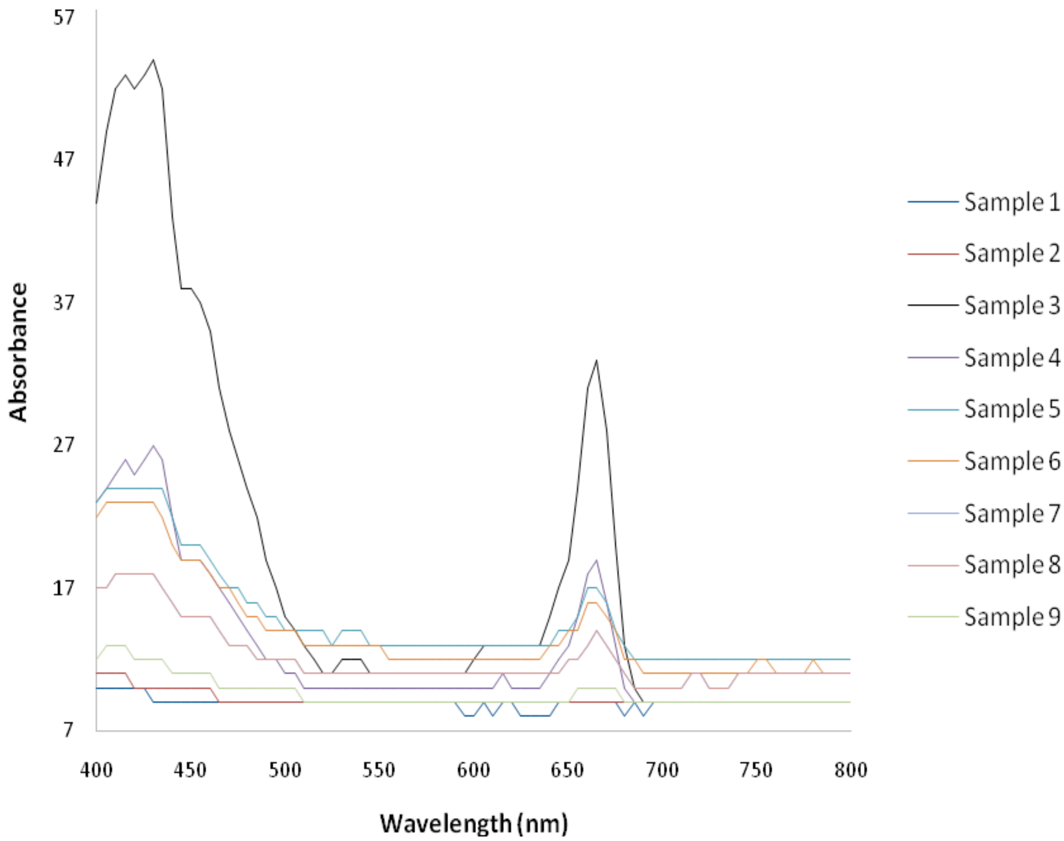
Indeed the justifications presented by A5 and A6 illustrate the difficulty of students to link concepts in the three modes coherently in their schemes of action, focusing predominantly on the macroscopic aspects of phenomena. However, it seems vital to stimulate the dialogue in the classroom to promote collective discussions with the aim of improving the schemes of action in all representation modes, bearing in mind that this is not a spontaneous capability of the students, as will be presented hereinafter.

Contribution of the Teacher and Format of the Collective Scheme Presented by the Students

With the purpose of inducing the development of invariants that allowed the students to establish relations between the sub-microscopic model and symbolic representation as well as to consider the co-occurrence of events in their models of explanations, during the third day of activities members of the different groups were asked to work together. Thus, student A3 (saccharose problem) and students A5 and A6 (silica problem) formed a new group. This strategy aims at comparing the data from different stationary phases. At this moment (M2), students should evaluate the efficacy of the chromatographic column based on the electronic spectra of the fractions. In order to make comparisons, the students possessed the visible light electronic spectra of chlorophyll, xanthophyll and b-carotene. Figure 1 shows the results of the chromatographic separations obtained by the students. The electronic spectra were important as a guide about the possible reasons why the use of silica as stationary phase resulted in a better separation of the components of the initial mixture – the core of the discussions at that moment.



A.



B.

Figure 1: Visible light electronic spectra of the chromatographic fractions obtained by the students: A – silica as stationary phase (students A5 and A6); B – saccharose as stationary phase (student A3).

Initially there were explanations about the procedure related to the use of the eluent polarity as an attempt to justify the preferential elution of b-carotene (student A5). It is worth mentioning that the group of students A5 and A6 decided to carry out a chromatographic column with a gradient elution, starting with a mixture of hexane:acetone 50:50 (v/v) and ending with an apolar mixture, 70:30 (v/v), which is not the standard procedure when carrying out a chromatography with gradient elution. Indeed, even though the elution strength of the mixture hexane:acetone 50:50 (v/v) is higher in comparison with 70:30 (v/v), the effectiveness of the silica hydrogen bridges with the substances in solution decreases due to the competition with the acetone molecules, consequently reducing the resolution of the chromatography. It is important to mention that these students did not take into account the arguments that considered the influence of the intermolecular interactions between the substances and stationary phase.

A5: chlorophyll and xanthophyll are polar so they will be eluted first... (0:01:51.5)

A5: we started with 50:50 of hexane and acetone, right? (0:02:01.1)

A5: so the chlorophyll and xanthophyll had to be eluted first and then the b-carotene because we decreased polarity... (0:02:15.7)

A3: I believe that our samples and the literature look similar because the first peak is between 400 nm and 500 nm...(0:03:08.2)

A6: and these two were the greener... (0:03:29.0)

A5: because initially the part of the green sample came and afterwards a yellow part, right? (0:03:37.9)

The construction of thinking continued to be based on macroscopic concepts supported by the concept of polarity when A3 brings the data of the saccharose chromatographic column:

A3: so I believe it also influences the... (0:15:36.8)

A5: speed of flow? (0:15:37.6)

A3: yes, because sugar particle size is higher than the particle size of the silica column... (0:15:44.5)

A5: so there was less contact of the sample in the column to the stationary phase, right? 0:15:50.0)

A3: maybe the decrease of polarity influenced the experiment... (0:17:00.0)

The comparison between experimental variables was more explicit when student A5 questioned if the silica was more polar than saccharose in an attempt to compare the efficacy of the different chromatographic columns. A3 contributed to the construction of sub-microscopic thinking by mentioning the differences in electronegativity between the oxygen and silicium atoms, consulting the teacher to confirm if it was a valid hypothesis.

A5: is the silica more polar than the sugar? (0:20:52.2)

A5: I thought it was the opposite, that the sugar was more polar than the silica... (0:20:59.0)

A3: polarity is connected with the presence of groups of electronegative atoms and the oxygen is more electronegative in both cases comparing silica with sugar, but its electronegativity is similar to the silicium... (0:21:47.3)

P: it is a difficult comparison because both have OH groups…the silic forms a polymeric structure and the saccharose does not…but it is difficult to compare the polarity because both are polar structures… But if you have a different variable that is the particle size...(0:23:15.2)

A3: we already agreed about this... (0:23:18.6)

P: I believe this is it... (0:23:23.9)

A3: it is more important... (0:23:26.1)

A5: than the issue of polarity... (0:23:28.2)

P: yes, because it will not be possible to compare... (0:23:29.9)

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Based on this approach, it should also be considered the influence of the teacher in the collective construction of the students in an attempt to promote relations of conceptual pertinence or making the operative invariants explicit (operations of thinking combined with comparisons, relations between macroscopic, sub-microscopic and symbolic representation, for instance). The data reported about the moment M2 suggest a glimpse of the construction of a collective scheme involving the teams of students and the teacher. The students reached a certain step of the construction of thinking; however, they needed the support of a more experienced subject to confirm the relations of pertinence of conceptual scope and to validate an implicit operative invariant: the pertinence of a hypothesis about polarity effects versus stationary phase particle size to explain the differences in efficiency of the chromatographic columns.

Even though the conceptual relations were temporary and not very thorough, the students relied on articulating concepts on the structural conceptual field (SCF) such as electronegativity and polarity after analysing chemical structures. On the other hand, despite frequently recurring to these concepts, the students involved at the moment M2 did not nominally (nor symbolic) considered the intermolecular interactions related to the pairs of *solute – stationary phase and solute – mobile phase*. This was a gap on their scheme and the teacher could have addressed it. Even though the intervention of the teacher had a different focus, it is possible to observe an increase in the use of conceptual contents on SCF after the moment the teacher talked to the students A3, A5 and A6 about the similarities and differences between the stationary phases.

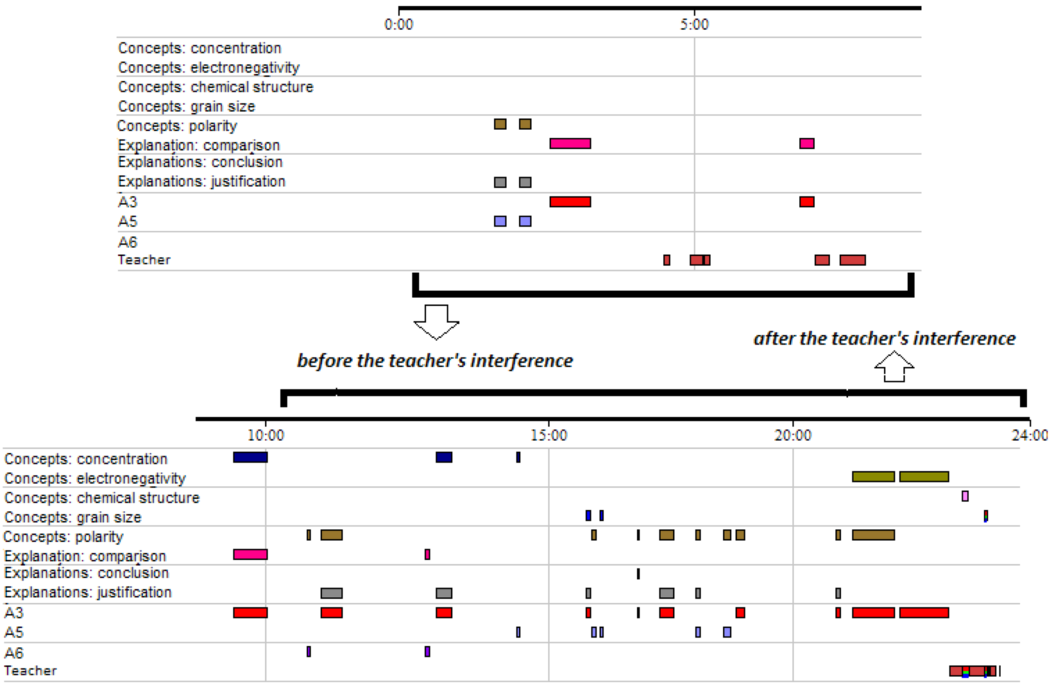

Figure 2: Structure of students' A3, A5 e A6 schemes before and after the intervention of the teacher.

Discussion

A central goal of this research was to identify which factors influence the mobilization of collective schemes by undergraduate students. Is the influence of the teacher fundamental in this process? Vergnaud (1990) proposes that the difficulty of students to resolve tasks is linked not to the type of operation that a task requires, but the operations of thought that students should do to establish appropriate relations between the data without losing view the relationship require some degree of conceptualization. The schemes are the way to solve the tasks that include concepts and operative invariants. A scheme can be individually presented with implicit and explicit factors of thinking. However, it is setting for an individual originally, not for a group.

Recent literature suggests there is the possibility of the development of a scheme in a collective environment. Marcel (2006) points out that individual action schemes can make up a collective pattern and be developed in a group with several individuals. According to this assumption, it would not be a simple combination of individual schemes. From the interaction with the tasks which mobilize concepts and operative invariants through the use of symbolic representations, a collective scheme could be consensually developed, and it would be necessarily possible to identify the individual schemes. Caballero, Moreira & Grings (2008) also consider that some situations can be resolved only the help of the teacher and classmates.

Conclusions

This research suggests that there is the collective construction of schemes characterized by a field of concepts in continuous motion. This perspective has an impact on the teacher should play a vital role in students' learning. Even though the students are active about the conceptual relations they should establish to cope with different situations, it is the teacher's responsibility to observe the gaps on the schemes and address them *in loco*. It is important to emphasize that these gaps are sensitive to didactic strategies and interactions between the pairs, thus, it is recommended:

i. Reorganizing the students in new working groups can be a path to create opportunities of negotiation in which some variables involved in the situations and not previously explored can be confronted in different modes – considering the structural conceptual field (SCF), in macroscopic, sub-microscopic and symbolic modes;

ii. Interacting with the students, thus identifying not only the quantity and pertinence of the conceptual relations they established, but also the *missing operative invariants* on their actions and explanations. *Establishing relations between the sub-microscopic mode and symbolic representation* and conceiving *the simultaneity of events* are operations of thinking important to the development of schemes that involve the structural conceptual field (SCF).

Acknowledgements

Acknowledgement to FAPESP (The São Paulo Research Foundation).

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Received: *November 09, 2015* Accepted: *December 12, 2015*

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