Chemistry Education Research and Practice

Accepted Manuscript

ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/cerp

Students' representations of the atomic structure – The effect of some individual differences in particular task contexts

George Papageorgiou*, Angelos Markos and Nikolaos Zarkadis,

Democritus University of Thrace, Greece

Abstract

The current study aims to investigate students' representations of the atomic structure in a number of student cohorts with specific characteristics concerning age, grade, class curriculum and some individual differences, such as formal reasoning and field dependence/independence. Two specific task contexts, which were designed in accordance with corresponding teaching contexts for the atomic structure, one based on Bohr's model and one on the quantum mechanical model, were examined as for their potential to differentiate initial students' representations of the atomic structure (when no specific context was provided). Participants (*n* = 421) were students of 8th, 10th and 12th grades of secondary schools from Northern Greece. Results showed that, although developmental factors, like formal reasoning, were associated with a better representation of the atomic structure, task context appeared to have the dominant role, since positive associations were found between student cohort characteristics and representation of the atomic structure in context dependent tasks, even after accounting for the effects of individual differences.

Keywords: Representations; Atomic structure; Context dependence; Individual differences.

Introduction

Despite the paramount importance of the idea of the atom and its structure, students are often not aware of it and their relevant ideas appear to be quite hazy. From an ontological perspective, the atom is often confused with a molecule, an ion or a cell and sometimes described as an unspecified entity of the microcosm (Cokelez, 2012; Cokelez and Dumon, 2005; Griffiths and Preston, 1992; Harrison and Treagust, 1996; Taber, 2003). Many students also consider the atom to be a living unit that can participate in biological functions, confusing its nucleus with the nucleus of the cell (Griffiths and Preston, 1992; Harrison and Treagust, 1996), whereas its size is described unclearly as 'too small', large enough to be seen in a microscope, similar to that of a molecule, a 'point of a needle', a 'head of a pin' or a dot (Cokelez, 2012; Griffiths and Preston, 1992; Harrison and Treagust, 1996).

Students' representations of the atomic structure

Due to the students' difficulty in perceiving the idea of the atom, many researchers have investigated relevant students' representations concerning the atom itself and its sub-atomic particles within a wide range of ages/grades and complexity, from the most simple and concrete to the most sophisticated and abstract quantum contexts (e.g., Adbo and Taber, 2009; Cokelez, 2012; Cokelez and Dumon, 2005; Fischler and Lichtfield, 1992; Harrison and Treagust, 1996, 2000; Kalkanis *et al.*, 2003; Nakiboglu, 2003; Papaphotis and Tsaparlis, 2008 ; Park and Light, 2009; Petri and Niedderer, 1998; Stefani and Tsaparlis, 2009; Stevens *et al.*, 2010; Tsaparlis and Papaphotis, 2002, 2009; Wang and Barrow, 2013). Systematic research generally begins around grades 6-7, where students' difficulty in representing the atomic structure is quite obvious and their representations usually comprise only a dot, a circle or a sphere without describing further details (Cokelez, 2012; Cokelez and Dumon, 2005; Griffiths and Preston, 1992; Harrison and Treagust, 1996; Stevens *et al.*, 2010). These representations are connected to the students' 'Particle model', where the atom is considered to be just a particle, without any other reference to microscopic characteristics (Cokelez, 2012; Park and Light, 2009). Moving to more detailed atomic structure considerations, researchers have identified models where students can represent the components of the atom, the compositional relationship between them and in some cases the existence of forces between them. These are reported as representations of the 'nuclear model' (Park and Light, 2009) or the 'composition atom model' (Cokelez, 2012; Cokelez and Dumon, 2005).

However, more interesting are the cases where student models comprise paths of electrons, either with or without references to certain levels of orbits and/or to energy quantization. These cases are reported mostly as the 'solar system model' (Cokelez, 2012; Cokelez and Dumon, 2005; Harrison and Treagust, 1996; Nakiboglu, 2003; Nicoll, 2001), the 'planetary model' (Adbo and Taber, 2009; Papaphotis and Tsaparlis, 2008; Petri and Niedderer, 1998; Tsaparlis and Papaphotis, 2009) or 'Bohr's model' (Fischler and Lichtfield, 1992; McKagan *et al.*, 2008; Nicoll, 2001; Papaphotis and Tsaparlis, 2008; Park and Light, 2009; Tsaparlis and Papaphotis, 2009; Wang and Barrow, 2013), and are considered to be the most typical ones in students' descriptions of the atomic structure. Even though these cases refer to scientifically and historically different models (Justi and Gilbert, 2000), in the majority of students' mental model categorizations as articulated by science education researchers, they have been treated as one and the same kind of deterministic model. For instance, Park and Light (2009) studied students' representations of the atomic structure. Although from a scientific point of view Bohr's model has been clearly based on quantum theory, the researchers incorporated all the above cases – even those without any references to quantum theory – into the same student model, i.e. 'Bohr's model'. Possible student references to certain levels of orbits and/or energy quantization were taken into account only in the formation of the corresponding sub-categories inside this model. Other researchers, when they similarly blend scientifically different models in order to form a particular student mental model, they use appropriate representative terms, such as 'planetary Bohr's model' (Tsaparlis and Papaphotis, 2009) or 'Bohr/solar system model' (Stevens *et al.*, 2010). In any case, this kind of mental model – let us refer to it as 'Bohr's model' - appears to be the most dominant in students' thinking, even in the upper grades of secondary education, where the conditions could probably facilitate the development of a more sophisticated approach to the atomic structure (Fischler and Lichtfeldt, 1992; Papaphotis and Tsaparlis, 2008; Petri and Niedderer, 1998; Tsaparlis and Papaphotis, 2009).

Towards a quantum description of the atomic structure, the literature shows more sophisticated students' representations that are reported as 'orbital model' (Harrison and Treagust, 1996; Kalkanis *et al.*, 2003; Taber 2005), 'electron cloud model' (Cokelez and Dumon, 2005; Cokelez, 2012; Petri and Niedderer, 1998; Stevens et. al., 2010; Tsaparlis and Papaphotis, 2009), 'quantum model' (Park and Light, 2009; Taber, 2002a, 2005) or 'Schrödinger model' (McKagan *et al.*, 2008). In these student models, concepts such as energy quantization, wave function or/and probability are frequently present. Similar to those reported above for 'Bohr's model', an incorporation of scientifically different relevant models into a particular student mental model has also been noticed – let us refer to it as the 'quantum mechanical model'. However, research has demonstrated that students generally have difficulties and hold misconceptions in adopting this model, since its understanding also requires an understanding of many other abstract concepts such as 'orbital' (Nakiboglou, 2003; Papaphotis and Tsaparlis, 2008; Stefani and Tsaparlis, 2009; Taber, 2002a,b, 2005; Tsaparlis, 1997; Tsaparlis and Papaphotis, 2002, 2009), 'electron cloud' (Harrison and Treagust, 1996, 2000; Tsaparlis and Papaphotis, 2002, 2009), 'quantization of energy' and 'angular momentum' (Didiş *et al.*, 2014; Taber, 2002a), 'probability' (Park and Light, 2009), 'Heisenberg's uncertainty principle' (Tsaparlis and Papaphotis, 2009) and other characteristics of a quantum probabilistic approach.

The effect of the context

The study of students' representations of the atomic structure has highlighted major problems in understanding, which appears to grow as one moves from 'Bohr's model' towards the 'quantum mechanical model'. However, these two models actually define two different teaching/learning contexts for the representations of the atomic structure and this transition from one model to the other appears to be problematic for students (e.g., Park and Light, 2009; Petri and Niedderer, 1998; Taber, 2005). In such a transition, students hold many of the characteristics of the former context and carry them over to the latter. As a result, they have difficulty, for instance, to integrate the concepts of shells and orbitals, as they use them interchangeably, (Nakiboglou, 2003; Nicoll, 2001; Stevens *et al.*, 2010; Taber, 2002a, 2005) or they confuse the electron cloud with the concept of a shell (Harrison and Treagust, 2000). From a teaching/learning perspective and in order to overcome these problems, Kalkanis *et al.* (2003) proposed an intensive juxtaposition of the two models during the introduction of the quantum mechanical model, presenting them as two entirely independent conceptual contexts, making thus students able to compare, differentiate and finally clearly articulate them. In addition, McKagan *et al.* (2008) suggest that, when a curriculum is designed with sufficient connections between such different models and enables students to compare and contrast the models, students may be better able to make a transition from Bohr's model to a more sophisticated one.

However, apart from the implications for the teaching/learning procedure, the idea that these two models (i.e. 'Bohr's model' and the 'quantum mechanical model') define two different contexts, has also implications for researchers trying to explore relevant students' representations. In the process of developing an appropriate research instrument and creating certain tasks, a researcher has the option to define a 'task context' with particular contextual features/settings, on which students could base their representations of the atomic structure. In other words, 'task context' refers to a set of situational settings in a specific area, in which cueing and prompting is given to students (Sağlam, 2010). The question here is: Could such a task context have a significant effect on the corresponding student's representation?

According to a number of studies, a 'task context' can generally affect student responses (e.g. Bao, Hogg and Zollman, 2002; Bao and Redish, 2006; Didiş *et al.,* 2014; Hrepic *et al.*, 2010; Itza-Ortiz *et al.*, 2004; Palmer, 1997; Petri and Niedderer, 1998; Redish and Smith, 2008; Sağlam, 2010; Teichert *et al.*, 2008). This is known as 'context dependence' (e.g. Redish and Smith, 2008; Bao and Redish, 2006) and it is also connected to the theory of 'knowledge in pieces' (diSessa, 1993). According to the latter, student responses to particular questions are based on the '*in situ*' combination of small pieces of knowledge that could produce inconsistent answers, since they are influenced by the contextual features of the questions. On this basis, when students are trying to work within two different task contexts towards a representation of the atomic structure, they could activate different knowledge resources, which would significantly differentiate their thinking. For example, in the study of Tsaparlis and Papaphotis (2009) on students' atomic representations, it appears that the context of the tasks during the interviews and the relevant discussions affected the high-school students' (12th grade) representations, leading those who initially provided simple model representations (e.g. Bohr model) to adopt a more sophisticated model (electron cloud model). Such context dependence could be affected by a number of factors. Wang and Barrow (2013), for instance, when investigated the undergraduate students' general chemistry conceptual frameworks about the atomic structure, found that 'high conceptual knowledge' (HCK) students were much more context dependent than 'low conceptual knowledge' (LCK) students. HCK students had the ability to adapt their representations of the atomic structure to the context of the task and thus, could switch from the Bohr model to the electron-cloud model using quantum mechanics descriptions in order to explain, for instance, the electron distribution of a polar bond. In contrast, LCK students could only work on simple models and had difficulties in using quantum mechanics descriptions in the context of the electron-cloud model.

Individual differences

The fact that student mental models of the atomic structure are distributed among a wide range of complexity, from the most concrete to the most abstract, suggests that students could also be affected by cognitive factors like individual differences. For instance, individual differences, such as in formal reasoning and field dependence/independence, have been found to be significant predictors of student performance in understanding the particulate nature of matter and the concept of chemical change (Stamovlasis and Papageorgiou 2012, Tsitsipis *et al.,* 2012, Kypraios *et al.*, 2014). However, to our knowledge, no study has investigated the effect of these cognitive factors on student mental models for the atomic structure.

Formal Reasoning (FR), also reported as *Logical Thinking*, is in fact a Piagetian concept and it refers to the ability of an individual to use concrete and formal operational reasoning (Lawson, 1978, 1985, 1993). In the general context of science education many studies have reported a correlation between FR and student performance (e.g. Chandran *et al.,* 1987; Lawson, 1982; Niaz, 1996). On the other hand, *Field Dependence/Independence* (FDI) is associated with the ability of an individual to disembed relevant information from a complex context or, in other words, the ability to efficiently separate the 'signal' from the 'noise' (Witkin *et al.*, 1971). In the literature, FDI appears to be very important for the conceptual understanding of science concepts (Bahar and Hansell, 2000; Danili and Reid, 2006; Kang *et al.*, 2005; Tsaparlis, 2005).

The atomic structure in Greek secondary education

In Greece, secondary education includes the lower secondary education, known as 'gymnasium' (grades 7, 8 and 9), and the upper secondary education, known as 'lyceum' (grades 10, 11 and 12), where the 12th grade consists of three directions, namely 'science and math', 'technological' and 'theoretical'. Students are taught the concept of the atom, its structure and relevant concepts in the context of chemistry, in both lower secondary (during 8th grade, age 13-14) and upper secondary education (during 10th grade and the 'science and math' direction of 12th grade, ages 15-16 and 17-18, respectively). The atomic structure and relevant concepts are also taught in the context of physics during all three directions of 12th grade. All the relevant courses last one year.

Particularly relevant to the context of chemistry, students in the 8th grade receive a one-hour lesson per week about (among others) the concept of the atom, the subatomic particles and their characteristics, as well as an introduction to Bohr's atomic model. In the 10th grade, during two one-hour lessons per week, students are taught the electronic configuration of the atom based on Bohr's atomic model. In the 12th grade, students in the 'science and math' direction also receive two one-hour lessons per week, where they are taught (among others) the quantum mechanical model and relevant concepts, such as the atomic orbital, the uncertainty principle, the electron cloud and its density.

In the context of physics, all students of the 12th grade receive a one-hour lesson per week, where they are taught (among others) more in-depth concepts related to the Bohr atomic model, such as the electron stimulation or the ionization.

Rationale of the study and research questions

Since 'context' appears to have a significant impact on students' understanding of various concepts, it would be interesting to investigate whether and how this impacts students' representations of the atomic structure. In particular, two 'task contexts' were designed in accordance with the two basic 'teaching/learning contexts' that are mainly used in secondary science education for the atomic structure, i.e. one based on Bohr's atomic model and the other based on the quantum mechanical model. The aim was to investigate the differentiations in students' representations when comparing their representations in these task contexts to the initial ones (where no specific task context has been given to work), in a number of student cohorts with specific characteristics concerning, apart from individual differences, such as formal reasoning and field dependence-independence, also age, grade and class curriculum. The aim of the study was to identify and compare students' representations of the atomic structure, when presented either with these two specific 'task contexts' or without context, taking also into account student cohort characteristics and individual differences.

With regard to individual differences, choices were theory driven considering also previous research findings. According to those, a number of Neo-Piagetian cognitive variables are identified as predictors of student achievement in science (Johnstone and Al-Naeme, 1995; Niaz, 1996; Tsitsipis *et al.*, 2010). Among them, formal reasoning and field dependence/independence were sought as closely associated with the tasks usually involved in the learning process related to science topics (Stamovlasis and Papageorgiou, 2012; Tsitsipis *et al.*, 2010), especially those for which 'context' is an issue.

Thus, the present study aims to investigate:

1. What are the students' representations of the atomic structure, in both the presence and absence of task context?

2. To what extent do cognitive factors (i.e. individual differences concerning formal reasoning and field dependence/independence) and student cohort characteristics (grade, age and curriculum) explain a possible variability in student competence for representing the atomic structure in the presence and absence of task context?

Taking into account recent relevant research evidence, a number of hypotheses could be articulated:

- *Hypothesis 1*: It is expected that task context will have a significant impact on students' representations of the atomic structure and consequently, representations will differ when the context changes.
- *Hypothesis 2*: It is expected that, dependently or independently of task context, an increase in the odds of possessing a scientifically sufficient representation will be associated with an increase in formal reasoning, field dependence/independence and student cohort characteristics (age and grade).
- *Hypothesis 3*: In line with the literature (e.g. Wang and Barrow, 2013), it is expected that student cohort characteristics will be associated with representations, even after accounting for the effects of cognitive factors.

Methodology

Subjects and Procedure

Participants were comprised of 421 students in 8th, 10th and 12th grades in secondary schools from Northern Greece. All schools were regular public ones, with mixed abilities classes and students from mixed socioeconomic background. All participants volunteered for taking part in the study. All classes participating in the study followed the National Science Curriculum for Greece (Greek Pedagogical Institute, 2003) using the same textbook for each one of the cohorts. Data were collected during the last semester of the school year through three paper-and-pencil tests (one for the atomic structure representations and two for the corresponding cognitive variables). Among the 421 participants, 189 were male (44.9%) and 232 female (55.1%), whereas the whole sample comprised students of the following four cohorts: 127 (30.2%) students of the 8th grade (age 13) as the first (1st) cohort, 167 (39.7%) students of the 10th grade (age 15) as the second (2nd) one, whereas the students of the 12th grade (age 17) fell in the third (3rd) and fourth (4th) cohorts, where 82 (19.5%) of them attended the 'technological direction' and 45 (10.7%) the 'science and math direction', respectively. Therefore, along with students' age, this grouping also reflects the educational direction ('science and math' or 'technological') and the corresponding science curriculum.

Instruments

A battery of paper-and-pencil assessments was created for the purposes of the study. This included measures of student background characteristics, two cognitive tests for assessing student individual differences, i.e. formal reasoning and field dependence/independence respectively, and an instrument designed to assess students' representations of the atomic structure.

Individual differences

The English versions of the cognitive tests were adapted and translated into Greek according to cross-cultural research guidelines (Beaton *et al.*, 2000). The original scoring system for the translated versions was maintained. A pilot study (n = 72) was carried out in order to detect and correct possible errors.

The construct validity of the two cognitive constructs was examined in the context of Confirmatory Factor Analysis (CFA). Due to the dichotomous/categorical nature of the test items (the correct and incorrect dichotomy was obtained by collapsing the options representing the wrong alternatives) the analysis was performed on the tetrachoric correlation matrix using the WLSMV (Weighted Least Squares with Mean and Variance Adjustment) estimator implemented in Mplus software Version 7.31 (Muthén and Muthén, 2015). Model fit was evaluated using the following indices: comparative fit index (CFI), Tucker-Lewis index (TLI), root mean square error of approximation (RMSEA), and 90% confidence interval (CI) of RMSEA. According to previous research, CFI and TLI values ≥ 0.95 and RMSEA values $\leq .08$, were considered as good indicators of the data–model fit (Hu and Bentler, 1999). Internal consistency of all measures was assessed using Cronbach's alpha coefficient. Scores for all scales used in the study were computed by summing the items that constitute the scale.

Field dependence/independence (FDI): The Group Embedded Figures Test was used to measure student field dependence/field independence (Witkin *et al*., 1971). The test requires the student to overcome misleading perceptual cues to dissembled simple figures concealed in complex ones. Lower scores indicate a field dependent learner; higher scores reflect a tendency toward field independence. The scale was treated as uni-dimensional, a structure which was replicated using CFA ($\chi^2(152) = 313.6$, $p < .001$, CFI = .98, TLI = .98, RMSEA = .050 [.042-.058]). In the current study, Cronbach's alpha reliability coefficient was found to be high (.84).

Formal Reasoning (FR): Students' formal reasoning abilities were measured using the corresponding Lawson paper-and-pencil test (Lawson, 1978). The test consists of 15 items involving the following: conservation of weight (1 item), displaced volume (1 item), control of variables (4 items), proportional reasoning (4 items), combinational reasoning (2 items) and probabilistic reasoning (3 items). The students were asked to justify their answers. Lawson (1978) estimated the reliability of the original test to be .78 and reported the original test to have face, convergent and factorial validity. For the present study, a uni-dimensional

CFA model demonstrated good fit ($\chi^2(84) = 105.4$, $p = .057$, CFI = .99, TLI= .99, RMSEA = .025 [.000-.038]) and coefficient alpha was .77.

Table 1 summarizes the descriptive statistics of each one of the cognitive scales.

Table 1. Descriptive statistics, Cronbach alphas and cognitive scale correlation

Scale	Mean	SD	Min	Max	FR	FDI
FR	7.19	3.06	0	15	(.77)	
FDI	8.59	4.58	0	20	$.49^{**}$	(.84)

Note. Cronbach's alpha reliabilities shown in parentheses

Students' representations of the atomic structure

Students' representations were investigated in the context of a wider study aiming their ideas on the atomic structure, in general. For the needs of this study, an instrument was developed in order to be used for all student cohorts. Among the total items of this instrument, three were developed for the assessment of the relevant students' representations, which were grouped into two distinct kinds of tasks; one, independently of any context (task 1) and one, in dependence of two specific contexts, i.e. Bohr's model and the quantum mechanical model (tasks 2a, 2b, respectively). A description of these tasks is presented in Table 2.

Students' representations were assessed in all tasks, taking into account both drawings and relevant feature descriptions, according to their correctness and completeness in comparison to the scientific view. Student scoring categorization took into account other similar categorizations already presented in relevant research (e.g., Cokelez, 2012; Harrison and Treagust, 1996; Park and Light, 2009). A summary of the categories for all tasks is presented in Table 3 together with the corresponding sub-categories. Category E refers to the most scientifically sufficient, whereas A refers to the most naïve.

Table 2. Description of the tasks and possible outcomes

Tasks	Kind of Task	Description of the tasks	Possible outcomes per task
1	Independent of any context	Students were asked to describe in details how they imagine the 'atom', if they could observe it through a 'powerful microscope', and to draw it	Students' representation of the atomic structure
2a	Dependent of the context	Students were asked to represent the atom based on the motion of the electron as a particle that can move in orbits (*Bohr's atomic model*)	Differentiations in relation to the initial student representations and within contextual features
2b		Students were asked to represent the atom if they imagine the electron as an electron cloud in various shapes (*quantum mechanical model*)	Differentiations in relation to the initial student representations and within new contextual features

In fact, the two contexts of tasks 2a and 2b could potentially lead students towards categories D and E, respectively. So, a shift from categories A, B and C to category D was expected in task 2a and a shift from categories A, B, C and D to category E in task 2b. Of course, this does not mean that all students shifting to D or E could fully understand the corresponding model, i.e. Bohr's model in task 2a and the quantum mechanical model in task 2b; what was assessed in that case, was the ability of students to adapt their representations of the atomic structure within the given characteristics of a specific context. A possible shift from E to D in task 2a could also not be excluded.

Table 3. Summary of students' representations of the atomic structure (scoring categories for all Tasks 1, 2a and 2b)

Category	Representation	Descriptions of sub-categories
A	*Atom-Cell model*	A_1.The atom as a cell with biological properties of a living organism.
B	*Particle model*	B_1. Reference to particles. No clarification if it is about atoms, molecules and ions.
		B_2. The atom as a circle, a ball or a sphere without reference to subatomic structure.
		B_3. The atom with unclear reference to subatomic structure.
C	*Nuclear model*	C_1. Nucleus, without a clear specification of the subatomic components.
		C_2. Nucleus with a clear specification of the subatomic components (e-, p, n).
		C_3. Nucleus with specifications and additional characteristics (mass, charge, etc.) of the subatomic components (e-, p, n).
D	*Bohr model*	D_1. Subatomic components and electron moving in circular orbits.
		D_2. Electron moving in specific shells, allowed circular or elliptical orbits, without references to quantization energy.
		D_3. Reference to shells and quantization of energy.
		D_4. Reference to shells, quantization of energy and an unclear reference to the concept of orbital.
E	*Quantum mechanical model*	E_1. Adoption of the ideas of the electron cloud and the orbital without abandon the particulate nature of the electron.
		E_2. Adoption of the ideas of the electron cloud and the orbital (no reference to the particulate nature of the electron)
		E_3. Adoption of the 'probability' for the nature of the electron without clarifying the type and the shape of an orbital.
		E_4. Adoption of the principles of Quantum Theory (probability, probability density, electron cloud and orbital etc) with forms of orbitals (s, px, py, pz, sp) and density of the electron cloud.

Statistical Analysis

Given that the outcome variables, i.e. tasks 1, 2a and 2b, represent non-interval level data, multivariate ordinal regression analysis was employed via GENLIN in SPSS to investigate hypotheses 1 and 2. Three separate models were evaluated. The ordinal variables corresponding to students' representations according to the three tasks (1, 2a and 2b) were used as the dependent variables. Main effects of formal reasoning, field dependence/independence, along with student cohort characteristics were entered into the models.

In order to investigate the influence of student cohort characteristics on students' representations, after accounting for the effects of cognitive variables (hypothesis 3), a Categorical Regression Analysis model (CATREG in SPSS) was examined with student cohort characteristics as the outcome and the two cognitive factors as the independent variables. The model residuals were subsequently correlated with students' representations using Kendall's tau-b correlation coefficient.

Results

Preliminary analyses

The distribution of representations of the atomic structure in tasks 1, 2a and 2b is presented in Table 4. When students represented atomic structure independently of any context (task 1), the nuclear and Bohr's models (categories C and D) were the most frequent, whereas the quantum mechanical model (category E) appeared only in 1.9% of the responses. When this percentage distribution was further analysed by student cohort (Table 5) for task 1, there was an increasing trend towards categories E and D, from the 1st to the 4th cohort. Taking into account what students had been taught in their classes per cohort and previous research evidence, these results were as expected.

With regard to the context dependent tasks (2a and 2b), shifts towards categories D and E were observed (Table 4). In task 2a, as expected, the majority of students appeared to be affected by the characteristics of the corresponding context and they represented the atomic structure according to Bohr's model (65.8%), although the nuclear model still held a significant percentage (26.6%). A closer look at the distribution per student cohort (Table 5) revealed that the effect of task context was greater in the 3rd and 4th cohorts, where 92.7% and 91.1% of students of each one of these cohorts, respectively, responded within the Bohr's model.

Interestingly, the effect of context on students' representations was even more obvious in task 2b, where the quantum mechanical model reached unexpectedly a percentage of 43.5% of the sample. The effect was even larger in the 4th cohort, reaching 93.3% of the students of this particular cohort. Taking into account the difficulty in perceiving the characteristics of this model, which also justifies the high percentage of missing values, these figures seem to be higher than expected. However, one should also take into account that this cohort included students who had been taught this model. In addition, as already mentioned, this does not mean that all these students have developed a good knowledge of the quantum mechanical model.

Table 4. Students' frequency (*n*) and percentage (%) distribution of representations of the atomic structure in tasks 1, 2a and 2b

	Task 1		Task 2a		Task 2b	
Category	*n*	%	*n*	%	*n*	%
A	16	3.8	3	.7	4	1.0
B	78	18.5	25	5.9	20	4.8
C	165	39.2	111	26.4	48	11.4
D	154	36.6	275	65.3	72	17.1
E	8	1.9	4	1.0	183	43.5
Missing	0	.0	3	.7	94	22.3
Total	421	100.0	421	100.0	421	100.0

Results of ordinal logistic regression

Three cumulative odds ordinal logistic regression models were fitted to determine the effects of formal reasoning, field dependence/independence and student cohort characteristics on representations of the atomic structure (tasks 1, 2a and 2b). The results are summarized in Table 6.

Table 5. Percentage (%) distribution of students' representations of the atomic structure in tasks 1, 2a and 2b by student cohort

	Task 1				Task 2a				Task 2b			
Category	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
A	4.7	5.4	1.2	.0	2.4	.0	.0	.0	2.4	.6	.0	.0
B	22.0	19.8	19.5	2.2	7.9	9.0	.0	.0	8.7	5.4	.0	.0
C	48.0	44.3	23.2	24.4	48.0	25.7	7.3	2.2	23.6	9.0	3.7	.0
D	25.2	29.9	54.9	60.0	39.4	64.7	92.7	91.1	16.5	15.0	31.7	.0
E	.0	.6	1.2	13.3	.0	.6	.0	6.7	36.2	35.3	43.9	93.3
Missing	.0	.0	.0	.0	2.4	.0	.0	.0	12.6	34.7	20.7	6.7
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 6. Results of the three cumulative odds ordinal regression models

	Task	Predictor	*Coef.*	*SE*	*OR*	95% *CI*		*Wald*	*p*
Independent	1	FR	.051	.010	1.052	1.033	1.072	28.277	<.001
		FDI	.070	.025	1.073	1.022	1.126	8.089	.004
		1st cohort	-1.308	.407	.270	.122	.601	10.303	.001
		2nd cohort	-1.540	.388	.214	.100	.458	15.777	<.001
		3rd cohort	-1.242	.407	.289	.130	.641	9.328	.002
		4th cohort*							
Dependent	2a	FR	.071	.012	1.074	1.048	1.100	32.842	<.001
		FDI	.059	.031	1.060	.998	1.126	3.625	.057
		1st cohort	-3.385	.826	.034	.007	.171	16.789	<.001
		2nd cohort	-2.783	.817	.062	.012	.306	11.616	.001
		3rd cohort	-1.512	.835	.220	.043	1.132	3.282	.070
		4th cohort*							
	2b	FR	.031	.009	1.032	1.013	1.051	10.963	.001
		FDI	.054	.025	1.055	.990	1.113	3.179	.069
		1st cohort	-2.353	.616	.095	.028	.318	14.584	<.001
		2nd cohort	-2.959	.606	.052	.016	.170	23.841	<.001
		3rd cohort	-2.671	.623	.069	.020	.234	18.410	<.001
		4th cohort*							

*Reference category

Note: Coef. = estimated coefficient B; SE = Standard error; OR = Odds Ratio; 95%CI = OR 95% confidence intervals

Task 1. For the first ordinal logistic regression model, the assumption of proportional odds was met, as assessed by a full likelihood ratio test comparing the residual of the fitted location model to a model with varying location parameters ($\chi^2(15) = 18.509$, $p > .05$). The deviance goodness-of-fit test indicated that the model was a good fit to the observed data ($\chi^2(1355) = 1042.25$, $p > .05$), but most cells were sparse with zero frequencies in 63.2% of cells. However, the final model statistically significantly predicted the dependent variable over and above the intercept-only model ($\chi^2(5) = 106.94$, $p < .001$). Results indicated that increases in formal reasoning and field dependence/independence were associated with an increase in the odds of possessing a sufficient representation of the atomic structure in task 1, with odds ratios of 1.052 (95% CI, 1.033 to 1.072), $\chi^2(1) = 28.277$, $p < .001$ and 1.073 (95% CI, 1.022 to 1.126), $\chi^2(1) = 8.089$, $p = .004$, respectively.

Student cohort characteristics had also a statistically significant effect ($\chi^2(3) = 15.820$, $p = .001$). Specifically, the odds for the 4th cohort (12th grade students - science and math direction) of possessing a sufficient representation of the atomic structure in task 1 were (1/.270) = 3.70 times greater than the odds for the 1st cohort (8th grade students), (1/.214) = 4.67 times higher than the odds for the 2nd cohort (10th grade students) and (1/.289) = 3.46 times higher than the odds for the 3rd cohort (12th grade students - technological direction). On the contrary, the odds of the 2nd cohort and the 3rd cohort were similar to those of the 1st cohort. Finally, the odds for the 3rd cohort were similar to those of the 2nd cohort. All the effects were found statistically significant.

Task 2a. For the second ordinal logistic regression model, the assumption of proportional odds was also met ($\chi^2(5) = 21.134$, $p > .05$) and the deviance goodness-of-fit test indicated that the model was a good fit to the observed data ($\chi^2(1351) = 485.482$, $p > .05$), but most cells were sparse with zero frequencies in 71.6% of cells. However, the final model statistically significantly predicted the dependent variable over and above the intercept-only model ($\chi^2(5) = 529.399$, $p < .001$). An increase in formal reasoning was associated with an increase in the odds of possessing a sufficient representation of the atomic structure in task 2a, with an odds ratio of 1.047 (95% CI, 1.026 to 1.069), $\chi^2(1) = 32.842$, $p < .001$. The effect of field dependence/independence was not statistically significant.

However, student cohort characteristics had a statistically significant effect ($\chi^2(3) = 27.230$, $p < .001$). The odds for the 4th cohort of possessing a sufficient representation of the atomic structure in task 2a were (1/.034) = 29.41 times greater than the odds for the 1st cohort, (1/0.062) = 16.12 times higher than the odds for the 2nd cohort and (1/.220) = 4.54 times higher than the odds for the 3rd cohort. The odds for the 2nd cohort were 1.82 times greater than the odds for the 1st cohort. Finally, the odds for the 3rd cohort were 4.54 and 3.56 times greater than the odds for the 1st and 2nd cohorts. All the effects were statistically significant.

Task 2b. For the third ordinal logistic regression model, the assumption of proportional odds was met ($\chi^2(5) = 12.849$, $p > 0.05$) and the deviance goodness-of-fit test indicated that the model was a good fit to the observed data ($\chi^2(1695) = 956.39$, $p > .05$), but most cells were sparse with zero frequencies in 69.1% of cells. However, the final model statistically significantly predicted the dependent variable over and above the intercept-only model ($\chi^2(5) = 85.753$, $p < .001$). An increase in formal reasoning was associated with an increase in the odds of possessing a sufficient representation of the atomic structure in task 2b, with odds ratios of 1.047 (95% CI, 1.026 to 1.069), $\chi^2(1) = 19.486$, $p < .001$. The effect of field dependence/independence was not statistically significant.

Student cohort characteristics had also a statistically significant effect ($\chi^2(3) = 12.899$, $p = .005$). The odds for the 4th cohort of possessing a sufficient representation of the atomic structure in task 2b were (1/.322) = 3.10 times greater than the odds for the 1st cohort, (1/.184) = 5.43 times higher than the odds for the 2nd cohort and (1/.223) = 4.48 times higher than the odds for the 3rd cohort. Moreover, the odds of the 2nd cohort were 1.95 times greater than that for the 1st cohort. Lastly, the odds for the 3rd cohort are 5.44 and 7.12 times greater than the odds for the 1st and the 2nd cohorts, respectively. All the effects were statistically significant.

Finally, the unique influence of student cohort characteristics on the representations of the atomic structure, after accounting for the effects of formal reasoning and field dependence/independence was investigated. For this purpose, the residuals of a categorical regression analysis model with cohort characteristics as the dependent variable and the two cognitive factors (FR and FDI) as independent were correlated with student performance in each of the three tasks, using Kendall's tau-b correlation coefficient. A non-significant correlation was detected for context independent task 1 (tau-b = .061, $p > .05$), whereas for context dependent tasks 2a and 2b the correlations were found positive and statistically significant (tau-b = .177 and tau-b = .192, $p < .01$). These results indicate, in the case of context dependent tasks, a positive association between student cohort characteristics and possessing a sufficient representation of the atomic structure, even after controlling for the effects of formal reasoning and field dependence/independence.

Discussion and educational implications

The effect of task context

Evaluating the results in relation to the main objectives of this research, a number of interesting discussion points emerge. Although the differences observed in students' representations of the atomic structure in relation to task context were expected to a certain degree, their importance is hiding in a careful examination of the results. In particular, when student representations were independent of any particular context, their distribution across the five models/categories indicates the dominance of classical and concrete descriptions of the atom against more abstract and sophisticated ones, in accordance with previous research evidence (e.g., Fischler and Lichtfield, 1992; McKagan *et. al.*, 2008; Petri, and Niedderer, 1998; Tsaparlis and Papaphotis, 2009). This is more evident within each one of the four cohorts, taking into account their characteristics and especially the preexisting students' knowledge according to the corresponding science curriculum. Despite the teaching of the quantum mechanical model in the 4th cohort, the student percentages in Bohr's category progressively increase from the 1st to the 4th cohort and only a small percentage of them responded within the quantum mechanical model. These results also indicate the powerfulness of Bohr's model as a didactic tool, which is useful for the students even in the upper grades of secondary education. As Harrison and Treagust (2000) suggest, when this kind of models is appropriately being used in the class, it can help students to better explore the corresponding approach of the atomic structure and it could be promising for further understanding of more abstract and sophisticated concepts.

With regard to hypothesis 1, it was expected that students' representations would change when students had to work within specific characteristics of particular task contexts. Indeed, the effect of such contexts was found significant for both tasks 2a and 2b. In the Bohr's context (task 2a) students reached very high percentages, which were higher than 90% in 3rd and 4th cohorts. Rather unexpectedly, it was observed that in task 2b (quantum mechanical context), students of the 4th cohort were not the only ones affected by the context (very high percentage, 93.3%), but significant percentages of students in the other cohorts were affected as well. Although possible implications for the corresponding teaching context is a big step ahead, one could make speculations for the possibility to have analogous effects on the adoption of more sophisticated models by students through an appropriately designed teaching/learning process. Relevant research provides evidence to this direction. Petri and Niedderer (1998) for instance, when differentiated the teaching context by setting different teaching inputs during a series of 80 appropriately designed lessons for the atomic structure, they found that, despite the domination of the planetary model in students' representations, different inputs had as a result the development of different conceptions for the atom, moving to a significant degree, from the planetary model to the electron cloud model.

The effect of individual differences

Apart from task context itself, individual differences also appeared to play an important role in the way in which students represented the atomic structure. Formal reasoning, as expected in hypothesis 2, and in accordance with already existing research evidence (Stamovlasis and Papageorgiou, 2012; Tsitsipis *et al.*, 2010; Tsitsipis *et al.*, 2012; Kypraios *et al.*, 2014), appeared to be the most important factor, dependently or independently of the context. Although the Piagetian theory has been many times under criticism, since it appears as a developmental theory rather than a learning theory, it seems that formal reasoning - which is a Piagetian concept - will always play an important role in the learning process. However, what is the most important here is that, unexpectedly and in contrast to hypothesis 2, the effect of field dependence/independence, although significant in the context independent task, was not found statistically significant in context dependent tasks. If one conveys this to the educational process, it could practically mean that an appropriately designed teaching context can possibly eliminate the effect of FDI, contributing to a better learning outcome.

Consequently, the findings concerning individual differences address to anyone who can configure the 'teaching context' and especially, to teachers and science curricula designers. As it has been suggested elsewhere (e.g., Stamovlasis and Papageorgiou, 2012), both of them can improve teaching outcomes, by adapting teaching context and relevant subject matter to the understanding level of the students of each grade and by using appropriately designed means, such as illustrations, diagrams, representations etc., in order to stimulate student attention on critical attributes of the atomic structure, especially when this is studied through more sophisticated models.

The effect of student cohort

Apart from individual differences, the collective characteristics of each one of the four student cohorts could also have an impact on students' representations of the atomic structure. As expected, our results support this hypothesis (hypothesis 3). In fact, student performance was found to significantly differ among all cohorts for the context dependent tasks, but only between the 4th cohort (12th grade, science and math direction, where students had received specific instruction regarding the quantum mechanical model) and all other cohorts in the case of the context independent task. More importantly, after controlling for the effects of formal reasoning and field dependence/independence, cohort characteristics were still positively associated with student performance, albeit only for context dependent tasks. What could this imply for the educational process, respectively? When working in a classroom without giving emphasis to the attributes of a particular context, a student with high performance in cognitive skills may have a higher probability to represent the atomic structure in a scientifically accepted way, independently of its cohort characteristics. However, when an appropriate teaching context is implemented in the classroom, the effects of individual differences are eliminated and the student cohort seems to play then the most determinative role. Therefore, the importance of context dependence in the learning process is again evident, indicating the significance of an appropriate science curriculum design in all grades.

Conclusions

According to the results of this study, although an escape from a Piagetian logic appears to be quite difficult dependently or independently of the context, the FDI factor does not have any effect on students' representations in context dependent tasks. More importantly, after controlling for FR and FDI, these representations are associated with student cohort characteristics only for context dependent tasks. Therefore, among a number of factors (task context, individual differences) that impact student representations of the atomic structure under particular circumstances, task context dependence plays the most dominant role. Consequently, these representations appear to be neither stable nor coherent as the theory of coherent models supports (e.g., Chi, 1992, 2005; Vosniadou and Brewer, 1992, 1994), but they are rather *'in situ'* constructions made by the combination of small size pieces of student knowledge in the contextual features of each task. The latter seems to be in accordance with the theory of 'knowledge in pieces' (diSessa, 1993). However, since these constructions could be affected by all the above factors, the present findings rather support the aspect of Taber (2008), who suggested that the question is not simply 'whether students' conceptions are coherent or not', but 'which conceptions within the context of a specific topic and under particular circumstances appear to be stable'.

As for the implications for the teaching and learning process, although the effect of 'task context' does not necessarily imply direct analogous effects of 'teaching context', some general considerations could be possibly made. In that context, it appears that, although developmental factors, like formal reasoning, will always play an important role in the learning process, having a significant effect on students' representations and conceptions in general, the success of this process is actually defined by the role of the teacher and the curricula designers. A science curriculum that takes into account student characteristics in each grade and an appropriate teaching methodology on the basis of a compatible context, could potentially overcome the challenges that arise by other factors, like FDI, and drive students through learning paths.

References

Adbo, K. and Taber, K. S., (2009), Learners' mental models of the particle nature of matter: a study of 16-yearold Swedish science students, *Int. J. Sci. Educ.,* **31**(6), 757–786.

Bahar, M. and Hansell, M., (2000), The relationship between some psychological factors and their effects on the performance of grid questions and word association tests, *Educ. Psychol.: Int. J. Exp. Educ. Psychol.*, **20**, 349-363.

Bao, L., Hogg, K. and Zollman, D., (2002), Model analysis of fine structures of student models: An example with Newton's third law, *Amer. J. Phys.*, **70**(7), 766-778.

Bao, L. and Redish, E. F., (2006), Model analysis: Representing and assessing the dynamics of student learning, *Phys. Rev. Spec. Top. Phys. Educ. Res.*, **2**(1), 010103.

Beaton, D. E., Bombardier, C., Guillemin, F. and Ferraz, M. B., (2000), Guidelines for the process of cross-cultural adaptation of self-report measures, *Spine*, **25**, 3186-3191.

Chandran, S., Treagust, D. F. and Tobin, K., (1987), The role of cognitive factors in chemistry achievement, *J. Res. Sci. Teach.*, **24**(2), 145-160.

Chi, M. T. H., (2005), Common sense conceptions of emergent processes: Why some misconceptions are robust, *J. Learn. Sci.,* **14** (2), 161-199.

Cokelez, A., (2012), Junior High School Students' Ideas about the Shape and Size of the Atom, *Res. Sci. Educ.*, **42**, 673–686.

Cokelez, A. and Dumon, A., (2005), Atom and molecule: upper secondary school French students' representations in long-term memory, *Chem. Educ. Res. Pract.,* **6**(3), 119–135.

Didiş, N., Eryılmaz, A. and Erkoç, Ş., (2014), Investigating students' mental models about the quantization of light, energy, and angular momentum, *Phys. Rev. Spec. Top. Phys. Educ. Res.*, **10**(2), 020127.

Danili, E. and Reid, N., (2006), Cognitive factors that can potentially affect pupils' test performance, *Chem. Educ. Res. Pract.,* **7** (2), 64-83.

diSessa, A. A., (1993), Toward an epistemology of physics, *Cognition Instruct.,* **10** (2 & 3), 105-225.

Engel, C. E. and Driver, R., (1986), A study of consistency in the use of students' conceptual frameworks across different task contexts, *Sci. Educ.*, **70**, 473–496.

Fischler, H and Lichtfield, M., (1992), Modern physics and students; conceptions, *Int. J. Sci. Educ.,* **14**(2), 181-190.

Greek Pedagogical Institute, (2003), *National Program of Study for Primary and Secondary Education: Science*, Athens (Greece): Greek Pedagogical Institute Publications.

Griffiths, K. A. and Preston, R. K., (1992), Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules, *J. Res. Sci. Teach.*, **29**(6), 611–628.

Itza-Ortiz, S. F., Rebello, S. and Zollman, D., (2004), Students' models of Newton's second law in mechanics and electromagnetism, *Eur. J. Phys.*, **25**(1), 81.

Harrison, A. G. and Treagust, D. F., (1996), Secondary students' mental models of atoms and molecules: implications for teaching chemistry, *Sci. Educ.*, **80**(5), 509–534.

Harrison, A. G. and Treagust, D. F., (2000), Learning about atoms, molecules, and chemical bonds: a case study of multiple-model use in grade 11 chemistry, *Sci. Educ.*, **84**(3), 352–381.

Hrepic, Z., Zollman, D. A. and Rebello, N. S., (2010), Identifying students' mental models of sound propagation: The role of conceptual blending in understanding conceptual change, *Phys. Rev. Spec. Top. Phys. Educ. Res.*, **6**(2), 020114.

Hu, L. T. and Bentler, P. M., (1999), Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives, *Struct. Equat. Model.*, **6**, 1–55.

Johnstone, A. H. and Al-Naeme, F. F., (1995), Filling a curriculum gap in chemistry, *Int. J. Sci. Educ.,* **17**(2), 219-232.

Justi, R. and Gilbert, J. K., (2000), History and philosophy of science through models: some challenges in the case of 'the atom', *Int. J. Sci. Educ.,* **22**(9), 993–1009.

Kalkanis, G., Hadzidaki, P. and Stavrou, D., (2003), An instructional model for a radical conceptual change towards quantum mechanics concepts, *Sci. Educ.*, **87**, 257-280.

Kang, S., Scharmann, L. C., Noh, T. and Koh, H., (2005), The influence of students' cognitive and motivational variables in respect of cognitive conflict and conceptual change, *Int. J. Sci. Educ.,* **27**(9), 1037-1058.

Kypraios, N., Papageorgiou, G. and Stamovlasis, D., (2014), The Role of Some Individual Differences in Understanding Chemical Changes: A study in Secondary Education, *Int. J. Envir. Sci. Educ.,* **9**(4), 413-427.

Lawson, A. E., (1978), Development and validation of the classroom test of formal reasoning, *J. Res. Sci. Teach.*, **15**, 11-24.

Lawson, A. E., (1982), Formal reasoning, achievement, and intelligence: an issue of importance, *Sci. Educ.*, **66**(1), 77-83.

Lawson, A. E., (1985), A review of research on formal reasoning and science instruction, *J. Res. Sci. Teach.*, **22**, 569-617.

Lawson, A. E., (1993), *Classroom test of scientific reasoning: revised paper-pencil edition. Tempe*, AZ: Arizona State University.

McKagan, S. B., Perkins, K.K. and Wieman, C. E., (2008), Why we should teach the Bohr model and how to teach it effectively, *Phys. Rev. Spec. Top. Phys. Educ. Res.*, **4**, 010103.

Muthén, B. and Muthén, L., (2012), *Mplus User's Guide* (7th ed.), Los Angeles, CA: Muthén and Muthén.

Nakiboglu, C., (2003), Instructional misconceptions of Turkish prospective chemistry teachers about orbitals and hybridization, *Chem. Educ. Res. Pract.,* **4**(2), 171-188.

Niaz, M., (1996), Reasoning strategies of students in solving chemistry problems as a function of developmental level, functional M-capacity and disembedding ability, *Int. J. Sci. Educ.,* **18**(5), 525-541.

Nicoll, G., (2001), A report of undergraduates' bonding misconceptions, *Int. J. Sci. Educ.,* **23**(7), 707-730.

Palmer, D., (1997), The effect of context on students' reasoning about forces, *Int. J. Sci. Educ.,* **19**(6), 681-696.

Papaphotis, G. and Tsaparlis, G., (2008), Conceptual versus algorithmic learning in high school chemistry: the case of basic quantum chemical concepts. Part 2. Students' common errors, misconceptions and difficulties in understanding, *Chem. Educ. Res. Pract.,* **9**(4), 332-340.

Park, E. J. and Light, G., (2009), Identifying Atomic Structure as a Threshold Concept: Student mental models and troublesomeness, *Int. J. Sci. Educ.,* **31**(2), 233–258.

Petri, J. and Niedderer, H., (1998), A learning pathway in high-school level quantum atomic physics, *Int. J. Sci. Educ.,* **20**(9), 1075–1088.

Redish, E. F. and Smith, K. A., (2008), Looking beyond content: Skill development for engineers, *J. Engin. Educ.*, **97**(3), 295-307.

Sağlam, M., (2010), University students' explanatory models of the interactions between electric charges and magnetic fields, *Educ. Res. Rev.*, **5**(9), 538-544.

Stamovlasis, D. and Papageorgiou, G., (2012), Understanding Chemical Change in Primary Education: The Effect of two Cognitive Variables, *J. Sci. Teach. Educ.*, **23**(2), 177-197.

Stefani, C. and Tsaparlis, G., (2009), Students' levels of explanations, models, and misconceptions in basic quantum chemistry: A phenomenographic study, *J. Res. Sci. Teach.*, **46**(5), 520–536.

Stevens, S. Y., Delgato, C. and Krajcik, J. S., (2010), Developing a hypothetical multi-dimensional learning progression for the nature of matter, *J. Res. Sci. Teach.*, **47**(6), 687-715.

Taber, K. S., (2002a), Conceptualizing quanta—illuminating the ground state of student understanding of atomic orbitals, *Chem. Educ. Res. Pract.,* **3**(2), 145 – 158.

Taber, K. S., (2002b), Compounding quanta: Probing the frontiers of student understanding of molecular orbitals, *Chem. Educ. Res. Pract.,* **3**(2), 159-173.

Taber, K. S., (2003), The atom in the chemistry curriculum: fundamental concept, teaching model or epistemological obstacle? *Foundat. Chem.*, **5**(1), 43–84.

Taber, K. S., (2005), Learning quanta: barriers to stimulating transitions in student understanding of orbital ideas, *Sci. Educ.*, **89**(1), 94–116.

Taber, K. S., (2008), Conceptual resources for learning science: Issues of transcience and grain-size in cognition and cognitive structure, *Int. J. Sci. Educ.,* **30**(8), 1027-1053.

Teichert, M. A., Tien, L. T., Anthony, S. and Rickey, D., (2008), Effects of context on students' molecular-level ideas, *Int. J. Sci. Educ.,* **30**(8), 1095-1114.

Tsaparlis, G., (2005), Non-algorithmic quantitative problem solving in university physical chemistry: a correlation study of the role of selective cognitive factors, *Res. Sci. Technol. Educ.,* **23**, 125-148.

Tsaparlis, G., (1997), Atomic and molecular structure in chemical education, *J. Chem. Educ.*, **74**(8), 922–925.

Tsaparlis, G. and Papaphotis, G., (2002), Quantum-chemical concepts: Are they suitable for secondary students? *Chem. Educ. Res. Pract.,* **3**(2), 129–144.

Tsaparlis, G. and Papaphotis, G., (2009), High-school students' conceptual difficulties and attempts at conceptual change: The case of basic quantum chemical concepts, *Int. J. Sci. Educ.,* **31**(7), 895–930.

Tsitsipis, G., Stamovlasis, D. and Papageorgiou, G., (2010), The effect of three cognitive variables on students' understanding of the particulate nature of matter and its changes of state, *Int. J. Sci. Educ.,* **32**(8), 987-1016.

Tsitsipis, G., Stamovlasis, D. and Papageorgiou, G., (2012), A probabilistic model for students' errors and misconceptions in relation to three cognitive variables, *Int. J. Sci. Math. Educ.,* **10**(4), 777-802.

Vosniadou, S. and Brewer, W. F., (1992), Mental models of the earth, A study of conceptual change in childhood, *Cognitive Psychol.,* **24**, 535-585.

Vosniadou, S. and Brewer, W. F., (1994), Mental models of the day/night cycle, *Cognitive Sci.,* **18**, 123-183.

Witkin, H. A., Oltman, P. K., Raskin, E. and Karp, S. A., (1971), *Embedded figures test, children's embedded figures test, group embedded figures test: manual*, Palo Alto, CA: Consulting Psychologists Press.

Wang, C. Y. and Barrow, L. H., (2013), Exploring conceptual frameworks of models of atomic structures and periodic variations, chemical bonding, and molecular shape and polarity: a comparison of undergraduate general chemistry students with high and low levels of content knowledge, *Chem. Educ. Res. Pract.,* **14**(1), 130-146.