Science Education International
32(2), 164-171
https://doi.org/10.33828/sei.v32.i2.10

REVIEW ARTICLE

Studying the Coherence of Students' Portrayed Representations of the Atomic Structure - Connections with Conceptions and Misconceptions

Nikolaos Zarkadis[1], Dimitrios Stamovlasis[2], George Papageorgiou[1]*

[1]Department of Primary Education, Democritus University of Thrace, Greece, [2]Department of Philosophy and Education, Aristotle University of Thessaloniki, Greece

***Corresponding Author:** gpapageo@eled.duth.gr

ABSTRACT

The present study investigated the association of students' fundamental ideas and misconceptions about ontological features of atom identity and behavior with the formation of their portrayed representations of the atomic structure. Participants (n = 421) were secondary education students in the eighth, tenth, and twelfth grades. Students' portrayed representations of the atomic structure were accessed through drawing tasks, while their understanding of the ontological features of atom was measured through a specially designed questionnaire. Latent Class Analysis (LCA), a psychometric method, was applied to the elementary features of the portrayed representations to classify them and test the potential coherence of their representations regarding atomic structure. The LCA revealed three latent classes, which showed a relative coherence in three of the anticipated models, "Particle model," "Nuclear model," and "Bohr's model." Moreover, students' conceptions and misconception about the ontological features of atom were used as covariates in the LCA and their effects on the above-mentioned class-memberships were estimated. Results indicated a significant effect of students' conceptions of the atomic ontological features on their portrayed representations of the atomic structure. Implications for theory and practice are discussed.

KEY WORDS: atom; latent class analysis; students' misconceptions

INTRODUCTION

Students' ideas for the atom and its structure have been widely studied in science education highlighting a number of various misconceptions that emphasize their insufficiency of the scientific knowledge (e.g., Cokelez and Dumon, 2005; Cokelez, 2012; Papageorgiou et al., 2016a; 2016b; Zarkadis et al., 2017; Allred and Bretz, 2019; Derman et al., 2019). Researchers have approached students' relevant knowledge covering a wide range of ages and grades from different perspectives, showing the multifaceted nature of this concept. Some have focused on specific ontological characteristics of the atom related to its identity and behavior, that is, distinction between atom identity and those of other submicroscopic particles or entities in general, its behavior during changes of states, atom animistic behaviors, etc. (e.g., Griffiths and Preston, 1992; Adbo and Taber, 2009; Cokelez, 2012; Papageorgiou et al., 2016b; Derman et al., 2019). Others have focused on atom portrayed representations, when identifying specific students' mental models (e.g., Papaphotis and Tsaparlis, 2008; Park and Light, 2009; Cokelez, 2012, Wang and Barrow, 2013; Papageorgiou et al., 2016a; Allred and Bretz, 2019; Derman et al., 2019). Regarding the former (concerning atom ontological characteristics), research evidence indicated that students often attribute macroscopic characteristics to atoms (e.g., Kikas, 2004; Adbo and Taber, 2009; 2014; Talanquer, 2009; Taber and García-Franco, 2010; Papageorgiou et al., 2016b; Derman et al., 2019). They show inability to distinguish between atom and other submicroscopic particles, that is, molecules or ions or they attribute animistic and anthropomorphic characteristics to atoms (e.g., Papageorgiou et al., 2016b). Regardingthe latter (students' portrayed representations of the atomic structure), a number of categories have been identified, which associated with particular mental models varying from the simplest and concrete to the most abstract and sophisticated (Cokelez and Dumon, 2005; Cokelez, 2012; Papageorgiou et al., 2016a; Zarkadis et al., 2017; Allred and Bretz, 2019; Derman et al., 2019). It has also been found that these portrayed representations are context dependent (e.g., Tsaparlis and Papaphotis, 2009; Wang and Barrow, 2013; Papageorgiou et al., 2016a; Zarkadis et al., 2017; Allred and Bretz, 2019).

In addition, there is evidence that the perceived ontological characteristics of the atom associated with its identity and behavior (as defined above) seem to influence students' portrayed representations (e.g., Griffiths and Preston, 1992; Harrison and Treagust, 1996; 2000; Cokelez, 2012; Papageorgiou et al., 2016b; Derman et al., 2019). However, there are no studies providing a more systematic and integrated view that supports and establishes a potential causal relationship between the former (ontological characteristics) and the latter (portrayed representations). In the present work, an attempt was made to further elucidate the above relationship by applying a robust psychometric method.

LITERATURE REVIEW

Students' Knowledge for the Atom

Among studies concerning students' knowledge for the atom, many focuses on atom identity and behavior, whereas others referred to portrayed representations of the atomic structure. As for the former, evidence from mostly textual students' descriptions suggests the existence of a significant number of misconceptions held by students of a wide range of ages (e.g., Griffiths and Preston, 1992; Harrison and Treagust, 1996; Nicoll, 2001; Kikas, 2004; Talenquer 2009; Adbo and Taber, 2009; 2014; Cokelez, 2012). These could be misconceptions concerning the attribution of macroscopic characteristics to the atom (e.g., Griffiths and Preston, 1992; Harrison and Treagust, 1996; Adbo and Taber, 2009; Talanquer, 2009; 2014; Derman et al., 2019). In this case, atoms of a substance have the same properties with the properties of the substance, for example, oxygen atoms are in gaseous state or iron atoms are in solid state. However, misconceptions could refer to a lack of distinction between the atom and other microscopic entities (i.e., cell) or submicroscopic particles (i.e., molecules or ions). Thus, atoms and molecules are treated as synonyms (e.g., Nicoll, 2001; Cokelez and Dumon, 2005; Papageorgiou et al., 2016b). For instance, water molecules are reported to consist of hydrogen and oxygen molecules, or "molecule" and "atom" are used interchangeably. Furthermore, the atom is reported to have similar size to that of a molecule or even an ion when they have the same number of protons (Griffiths and Preston, 1992; Eymur et al., 2013); whereas, in other cases, the size of the atom is like a "point of a needle" or a "head of a pin"s (Harrison and Treagust, 1996; Cokelez, 2012). As for the lack of distinction between atom and cell, atoms are reported to be made of cells or to have properties of living organisms and biological functions (e.g., Cokelez, 2012; Harrison and Treagust, 1996). Thus, there are many times where students attribute animistic and anthropomorphic characteristics to atoms, with an atom capable of feeling, needing, wanting, being happy, etc. (e.g., Harrison and Treagust, 1996; Nicoll, 2001; Taber, 2003; Cokelez, 2012; Papageorgiou et al., 2016a; 2016b).

Students' ideas for the atom characteristics related to its identity and behavior seem to affect their portrayed representations of the atomic structure. Sporadic evidence showed that often, students represent an atom as group of atoms, denoting lack of distinction between particles (e.g., Cokelez and Dumon, 2005). In other cases, they represent the atom as a dot, a circle or a sphere, indicating the existence of difficulties concerning the atom size (e.g., Park and Light, 2009; Cokelez, 2012), or as an entity having a nucleus with functions similar to those of a cell (confusion between atom and cell, e.g., Harrison and Treagust, 1996). A general scheme founded in a review of the literature, suggests that students' representations of the atomic structure could be included in five mental model categories (Zarkadis et al., 2017). This categorization, from the simpler to the most sophisticated, model holds as follows: The simplest, that is usually called "particle model," is the one where the atom is considered to be a particle without further specifications (e.g., Harrison and Treagust, 1996; Cokelez and Dumon, 2005; Park and Light, 2009; Papageorgiou et al., 2016a). When characteristics of a living organism are assigned to the atom and the atom seems to be similar to a cell, then a second category arises, that of "atom–cell model" (e.g., Harrison and Treagust, 1996; Cokelez, 2012; Papageorgiou et al., 2016a). The "nuclear model" is the next category, where students include the components of the atom in their representations (e.g., Park and Light, 2009; Papageorgiou et al., 2016a), and for this reason the category is also reported as 'composition atom model' (e.g., Cokelez and Dumon, 2005; Cokelez, 2012). The next more sophisticated category includes all representations comprising paths of electrons, either with or without references to certain levels of orbits or energy quantization. This is in fact a wide category, which is known by a variety of terms such as, "solar system model" (e.g., Harrison and Treagust, 1996; Nakiboglu, 2003; Cokelez and Dumon, 2005; Cokelez, 2012), "planetary model" (e.g., Papaphotis and Tsaparlis, 2008; Adbo and Taber, 2009), or "Bohr's model" (e.g., Papaphotis and Tsaparlis, 2008; Park and Light, 2009; Wang and Barrow, 2013; Papageorgiou et al., 2016a). The most sophisticated category is that, in which students represent the atomic structure in a probabilistic way, considering the quantum theory. Mental models that fall into this category are reported, for instance, as the "orbital model" (e.g., Harrison and Treagust, 1996; Taber, 2005), the "electron cloud model" (e.g., Cokelez and Dumon, 2005; Cokelez, 2012), or the "quantum (mechanical) model" (Taber, 2002; 2005; Park and Light, 2009; Papageorgiou et al., 2016a).

Coherency Issues of Mental Models

Despite the existence of the five categories of student models for the atomic structure described above, recent studies indicate that they are not necessarily stable (e.g., Tsaparlis and Papaphotis, 2009; Papageorgiou et al., 2016a; Zarkadis et al., 2017). For instance, in a study by Papageorgiou et al. (2016a), the contextual features of a question/task seem to be able to affect students' models and their relevant portrayed representations, highlighting that a "*context dependence*" issue exists here (e.g., Bao and Redish, 2006; Redish and Smith, 2008). In addition, in another study, students' models seem to be inconsistent when they use atomic models to explain everyday situations. This inconsistency is apparent, not only *between* the models when they switch from a model to another, but also within a particular model when they use characteristics of another model (Zarkadis et al., 2017).

The apparent inconsistency among relevant portrayed representations is, in fact, part of the coherency of the mental model issue, a debate that has taken place in science literature for decades. On the one hand, there is the perspective supporting the existence of coherent mental models in students' minds (e.g., Ioannides and Vosniadou, 2002), which maintains support by

Science Education International
32(2), 164-171
https://doi.org/10.33828/sei.v32.i2.10

part of the research community. On the other hand, there is the "fragmented knowledge" or "knowledge in pieces" perspective (e.g., diSessa, 1993; diSessa et al., 2004), according to which, mental models are formed by the combination of smaller cognitive units (pieces of knowledge) that are activated "*in situ*' when a particular phenomenon or a situation should be explained. A compromising preposition tentatively suggested that student models could be seen by a researcher as consistent or inconsistent depending on the particular topic or the general context that is studied (e.g., Hammer, 1996; Taber, 2008; Taber and García-Franco, 2010). However, theory is tightly related to methodology supporting the empirical evidence, and this has been demonstrated lately for this issue by several investigations, where suitable statistical tools have been applied for detecting the degree of coherency in students' mental models (Straatemeier et. al., 2008; Stamovlasis et. al., 2013; Zarkadis et. al., 2017; Vaiopoulou and Papageorgiou, 2018). These endeavors established a methodology, a person-centered approach, which is based on an advanced psychometric modeling, which detects the degree of coherency, if any, of the mental models under study via the consistency of students' responses on selected questions or tasks.

RATIONALE AND RESEARCH QUESTIONS

The literature review presented in the previous sections highlights the need for further research on students' conceptions and misconceptions about atom and their associative role as antecedents or predictors of students' representations of the atomic structure portrayed on drawings. This hypothesis demands strong empirical evidence via a robust statistical approach and a detailed description of the relationships in question would be illuminating. Given that in this field most research is based on theoretical and epistemological assumptions, which consider students' naïve knowledge before they attain the science view, as categorical (i.e., coherent mental models, e.g., Vosniadou and Brewer, 1994), it is pertinent to consider the modeling and measurement procedures (Bartholomew et al., 2011). Methodologically, in this case, the effectiveness of the traditional statistical linear models (e.g., the factor model) is limited by the assumptions of normality and linear relationships, and their inappropriateness becomes obvious providing that the observables be measured at the nominal level. The present research applied "Latent Class Analysis" (LCA), an advanced psychometric modeling method, where both latent and observable variables are categorical. Discussions on the advantages of this method and its applicability in science education research can be found elsewhere (Stamovlasis et al., 2013; 2018). The LCA is applied using elements of portrayed representations of the atomic structure as input and the variables reflected students' conceptions and misconception of the atom (as identity and behavior), as covariates. In addition, based on the consistency of students' responses, the resulted latent classes as portrayed representations of the atomic structure are examined for their coherency.

Thus, the following research questions were investigated:

1. Are students' portrayed representations of the atomic structure coherent?
2. To what extent can students' ideas and misconceptions for the ontological features of atoms' identity and behavior, as well as cohort characteristics/age, affect their portrayed representations of the atomic structure?

METHODOLOGY

Sample and Procedure

The participants (n = 421, 55.10% female) were students in the 8th, 10th, and 12th grades of secondary schools from Northern Greece participated in the study on a voluntary basis, according to the ethical standards. Informed consent was obtained from the heads of the participating schools, the teachers of all classes and the students before the study. The sample consisted of four age-cohorts, as follows: The 1st cohort consisted of 127 students in grade 8 (30.2%, students aged 13), the 2nd consisted of 167 students of grade 10 (39.7%, age 15), the 3rd one of 82 students of grade 12, "technological direction" (19.5%, age 17), and the 4th consisted of 45 students of grade 12, "science and math direction" (10.7%, age 17). All students of the same cohort used the same textbook following the National Science Curriculum for Greece (Greek Pedagogical Institute, 2003). The textbook of the 3rd cohort emphasized the atom approach through the Bohr model, whereas that of the 4th cohort emphasized this approach through the quantum mechanical model. Students were from mixed socio-economic levels and attended mixed ability classes in regular public schools. Data were collected during the second semester of a school year, through a paper-and-pencil test designed to assess both students' ideas of the atom ontological characteristics and students' portrayed representations for the atomic structure.

Instruments

Accessing students' portrayed representations for the atomic structure was achieved via a questionnaire, which was part of an instrument specially designed to assess both students' ideas for the ontological features of atom as identity and behavior (1st Part) and their portrayed representations of the atomic structure (2nd Part). Note that the present study was a part of a wider one aiming to investigate students' mental models of the atom and their properties. Since other parts have already been published, details and validity issues about the tests and the selected items can be found elsewhere (see Papageorgiou et al., 2016a; 2016b). Note also, that the issue of reliability defined, as internal consistence among responses, was part of the hypotheses, since the assumed coherency of the mental models was measured as consistency of students' answers across varying contexts.

The instrument consists of two parts:

1st Part: Regarding the four tasks concerning students' ideas for the ontological features of atoms' identity and behavior, Table 1 shows what students were asked to textually explain and/or justify per task:

Science Education International
32(2), 164-171
https://doi.org/10.33828/sei.v32.i2.10

Students' answers were categorized as follows:

- Category "ScieView:" Scientifically accepted responses
- Category "M:" Misconceptions
- Category "NR:" Unclear responses or no response.

In the category M, the following misconceptions are included: The atom is thought to be a living organism with relevant functions (particle-cell confusion); the atom, the molecule, and the ion are thought to be synonyms (no distinction between particles); the atom is thought to be the only fundamental particle (ontological priority of atoms); and the atom is thought to be a compact unit, unchangeable under any change; the atom have macroscopic and/or anthropomorphic characteristics (Zarkadis et al., 2020).

2nd Part: Regarding the three tasks concerning students' portrayed representations of the atomic structure, students were asked to describe in detail how they imagined the "atom" if they could observe it through a "powerful microscope" and draw it, within specific contexts, as Table 2 shows:

Considering both drawings and relevant feature descriptions, students' responses were categorized in the five categories presented in the theoretical section of this paper (Students' knowledge for the atom), as follows:

- Category "*Atom-cell model*"
- Category "*Particle model*"
- Category "*Nuclear model*"
- Category "*Bohr's model*"
- Category "*Quantum model*".

In both Parts, the corresponding coding schemes were validated by two researchers and any discrepancy was thoroughly discussed until a complete agreement was reached.

Statistical Analysis-LCA

LCA is a cluster analysis method designed to identify clusters or latent classes, that is, groups of students, which share similar response patterns. These similar sets of responses are considered to originate from the same latent variable, which is the common causal-cause of the observable categories (McCutcheon, 1987; Clogg, 1995). LCA is a model-based cluster analysis and a psychometric modeling procedure, which implements the conditional probabilities (CP) for assigning class-memberships to participants. CP is the probability of providing a certain pattern of responses given that the cases belong to a specific group. The LC classification procedure provides several cluster solutions from which the researcher choses the most fit and the most interpretable solution. The model-solution goodness-of-fit is based on several indicators: the number of parameters, entropy-R^2, likelihood ratio statistic (L^2), Bayesian Information Criterion (BIC), Akaike's Information Criterion, degrees of freedom, and bootstrapped p-value. An additional valuable feature of LCA is that analysis of covariates could be included and determine the effects of the ensuing class memberships on external variables (Bakk et al., 2013).

Table 1: The four tasks concerning the ontological features of atoms' identity and behavior

Task	Explanations and/or justifications requested
1	What differences are, if any, when using the words "atom," "molecule," and "ion"
2	Whether "atoms" are/could be alive
3	What differences are, if any, between iron atoms in solid and liquid states
4	What differences are, if any, between oxygen atoms and iron atoms

RESULTS

In the LCA analysis, the set of Tasks 5, 6, and 7 of Part 2 was used. The LCA lead to a three-class solution ($R^2 = 0.95$, df = 38, classification-error = 0.0015, BIC = 1833.48, $N_{par} = 86$) as the best parsimonious model with the lower BIC values (Table 3). In the ensued clusters, the coherency of students' mental representation of atomic structure can be accessed through the depicted consistency of students' drawings across tasks.

Table 4 shows the three clusters and the corresponding CP, whereas Figures 1-3 show the cumulative CP for each cluster and depict the homogeneity of each cluster in term of atom model representations. Students' atom representations show a consistency, to some degree, that is, a particular prevailing response patterns appeared in each cluster. Cluster 2 (accounting of 23.68% of the sample) and Cluster 3 (accounting of 7.24% of the sample), the nuclear model and the particle model dominate correspondingly, whereas in Cluster 1 (where most of the sample belongs, 69.09%), although the Bohr's model seems to dominate, Quantum model appears with high CP in Task 7.

The effect of ontological misconceptions of the atom on the portrayed representations of the atomic structure was

Table 2: The three tasks concerning portrayed representations of the atomic structure

Task	Contexts given for the descriptions and drawings of the atomic structure
5	No context
6	Context of the Bohr's atomic model, imagining the electron as a particle that can move in orbits
7	Context of the quantum mechanical model, imagining the electron as an electron cloud in various shapes

Table 3: LCA solutions and the model fit indexes for Part 2 (Tasks 5, 6, and 7)

Solution	LL	BIC (LL)	N_{par}	L^2	df	p-value	Class. Err.	R^2
1-Cluster	-1047.7	2164.8	12	536.0	112	0.00	0	-
2-Cluster	-864.9	1874.3	25	170.3	99	0.00	0.0009	0.92
3-Cluster*	-806.8	1833.5	38	54.2	86	0.10	0.0015	0.95
4-Cluster	-793.8	1882.5	51	28.0	73	0.06	0.0016	0.90
5-Cluster	-784.6	1939.5	64	9.8	60	0.03	0.0252	0.91

Science Education International
32(2), 164-171
https://doi.org/10.33828/sei.v32.i2.10

Table 4: The three clusters and the corresponding CPs of Part 2

Categories per task	CPs for Cluster 1 (Cluster Size 0.6909)	CPs for Cluster 2 (Cluster Size 0.2368)	CPs for Cluster 3 (Cluster Size 0.0724)
Task 5			
Atom-cell model	0.0045	0.0258	0.3406
Particle model	0.0667	0.2184	0.6047
Nuclear model	0.3066	0.7539	0.0486
Bohr model	0.5867	0.0018	0.0058
Quantum model	0.0356	0.0001	0.0003
Task 6			
Atom-cell model	0	0	0.1273
Particle model	0.0001	0.0002	0.6789
Nuclear model	0.0006	0.9948	0.1833
Bohr model	0.9815	0.0049	0.0103
Quantum model	0.0178	0.0001	0.0002
Task 7			
Atom-cell model	0	0.0001	0.1697
Particle model	0.0001	0.0003	0.7635
Nuclear model	0.0047	0.6094	0.0025
Bohr model	0.3022	0.0373	0.0543
Quantum model	0.6931	0.3529	0.010

CP: Conditional probabilities

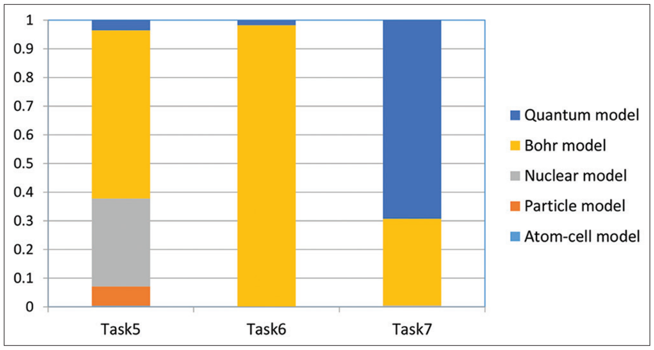

Figure 1: Conditional probabilities for Latent Class 1/Cluster 1 (69.09%)

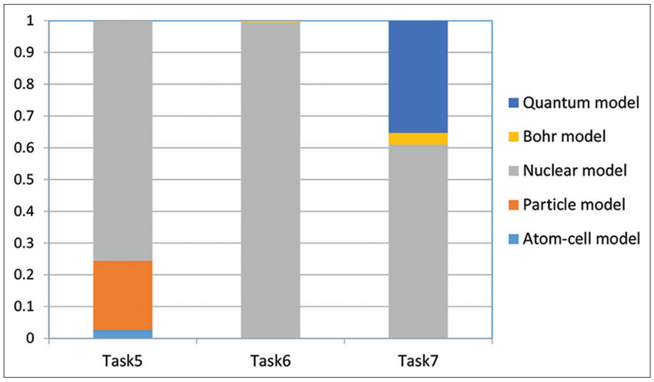

Figure 2: Conditional probabilities for Latent Class 2/ Cluster 2 (23.68%)

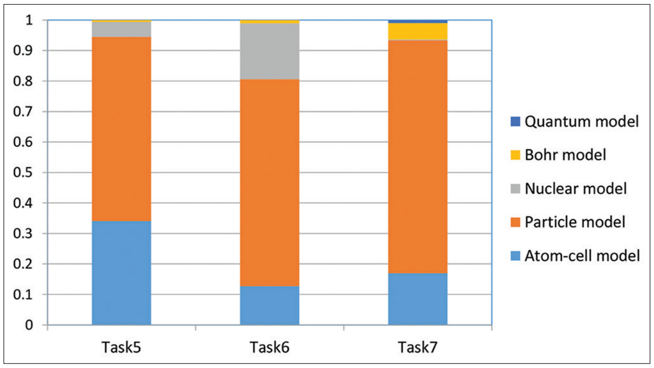

Figure 3: Conditional probabilities for Latent Class 3/ Cluster 3 (7.24%)

investigated by applying LCA with covariates, where students' responses in Part 1 were implemented as predictors of the Latent Class memberships ensuing from the LCA of the selected five atomic models (Part 2), which were used as dependent variables. The results are depicted in Table 5. It shows that Cluster 1, in which the Bohr's model seems to dominate (with Quantum model) associates negatively with "No Responses" and "Misconceptions," while it associates positively with the correct/science view conceptions of the atom. Cluster 2 in which the nuclear model dominates, does not associate significantly in most cases except in Task 4 (positive effect of correct answers) and Task 3 (negative effect of "No Responses"). Cluster 3 in which the Particle model dominates, it associates positively with "No Responses" and "Misconceptions" and negatively with the correct/science view conception of the atom.

In addition, the relative fractions of each cohort within the three Clusters are depicted in Figure 4, while cohort as covariate had a statistically significant effect on cluster memberships ($b = 0.83$, $\rho < 0.0001$).

DISCUSSION AND CONCLUSIONS

Findings concerning the consistency of students' portrayed representations of the atomic structure, according to the

Science Education International
32(2), 164-171
https://doi.org/10.33828/sei.v32.i2.10

Table 5: Effects of misconceptions about atomic structure on clusters membership (Part 2)

Task	Covariates	Cluster 1	Cluster 2	Cluster 3	Wald	ρ-value
Task 1	No response	−0.477*	0.018	0.459**	14.71	<0.01
	Misconception	0.518**	−0.204	−0.314**		
	Correct	0.042	0.187	−0.145		
Task 2	No response	−0.216	−0.210	0.426***	19.18	<0.001
	Misconception	−0.221*	0.013	0.208		
	Correct	0.437***	0.197	−0.634		
Task 3	No response	−0.217	0.310*	−0.093	14.74	<0.01
	Misconception	−0.107	−0.267	0.374**		
	Correct	0.324**	−0.043	−0.281**		
Task 4	No response	−0.214	−0.318	0.532***	18.02	<0.001
	Misconception	−0.013	0.043	−0.031		
	Correct	0.226*	0.274*	−0.501***		

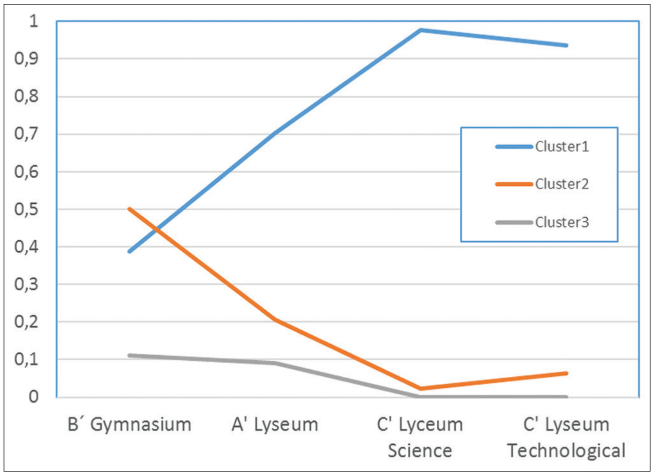

Figure 4: The relative fractions of each cohort within the three clusters

design of Part 2, seem to be quite interesting. Although it was expected that students' responses would demonstrate a context dependence (e.g., Bao and Redish, 2006; Redish and Smith, 2008; Papageorgiou et al., 2016a), interestingly, Clusters 1, 2, and 3 (Figures 1-3) provide evidence for some coherency and simultaneously a departing trend in student responses regarding their mental models. Specifically, in Cluster 1 (69.09%, Figure 1) most of the students dominated by the Bohr's model also show a propensity to evoke the quantum model when context was apposite. For students of the 3rd cohort, this could be also justified by the corresponding teaching context of "science and mathematics direction" within the quantum model (e.g., Kalkanis et al., 2003; McKagan et al., 2008). In Cluster 2 (23.68%, Figure 2), students dominated by the nuclear model also show a small propensity towards the quantum model when context was suitable. In Cluster 3, students were dominated by the particle model (Cluster 3, 7.24%, Figure 3). Thus, on the one hand, Clusters 2 and 3 probably highlight students' preference for more simple and concrete models (e.g., Harrison and Treagust, 1996; Cokelez and Dumon, 2005) over more complex and abstract ones. The dominance of one model in each cluster across the tasks (5, 6, and 7) even though it seems to be in contrast with the previous studies, where there was an inconsistency within and between students' mental models of the atom (Zarkadis et al., 2017; Zarkadis and Papageorgiou, 2020), is interpretable when considering the contingent framework of the two inquiries.

The focus of the present study was on the portrayed representation of the atomic structure itself, which was taught more in-depth within the Bohr model according to the class curriculum of each one of the 1st, 2nd, and 3rd (technological direction) cohorts, whereas students of the 4th cohort (science and math direction) were taught more in-depth the quantum model. On the contrary, the focus in the study by Zarkadis et al. (2017) was on students' decisions in adopting a model for atomic structure to explain everyday situations, something that had not been explicitly studied in schools and any students' familiarity was due to their everyday experience. Such findings indicating consistency in some case and inconsistency in another, regarding students' mental models, bring to the foreground the theoretical stance of some researchers (e.g., Hammer, 1996; Taber, 2008; Taber and García-Franco, 2010) according to which, students' mental models could be witnessed as consistent or inconsistent depending on the particular topic under study and the contingent framework. At this point it is imperative to stress that principal message from the present endeavor was the robust methodology implemented, which in fact, as has been emphasized elsewhere (see Stamovlasis et al., 2013), has opened a new avenue of investigations in testing the coherence hypothesis in students' mental structures.

It is remarkable that students of Cluster 1 (the majority of them), who spontaneously had a quite high CP to represent the atomic structure within the Bohr's model (58.67%, Task 5), they reached a 98.15% probability for such a representation when the context was apposite (Task 6). However, although retaining a 30.22% probability for the same (Bohr's) model in Task 7, students increased the probability of the quantum model to 69.31% (Task 7) to adapt their portrayed representation to the quantum model context (Table 5). This suggests one more time that the Bohr's model is the dominant one in secondary education (e.g., Papaphotis and Tsaparlis, 2008; Tsaparlis and Papaphotis, 2009), but it indicates the significant possibility to change the way students represent the atomic structure into a quantum one when the context was suitable.

Such a possibility to change the way students represent the atomic structure is manifested to a lesser degree when examining students in Cluster 2. As Table 4 and Figure 2 show, students who have a high probability to represent the atomic structure within the *nuclear model* (75.39% of Cluster 2, Task 5), can reach a 99.48% probability for such a portrayed representation within the context of the Bohr's model, whereas retain a high probability (60.94%) for the same representation within the context of the quantum model, having only a probability of 35.29% to adapt their representation to the quantum model. This suggests that these students cannot

Science Education International
32(2), 164-171
https://doi.org/10.33828/sei.v32.i2.10

easily understand the differences between nuclear and Bohr's model, whereas, when the context becomes even more different (quantum model), only few of them can change their portrayed representations. Possible explanations for such students' difficulties in distinguishing between the Bohr's and nuclear model could be based on their weakness to understand the sub-atomic interactions and the Coulombic principles (e.g., Taber, 2003; 2013; Wang and Barrow, 2013), as well as their relation to the centripetal force applied to the orbiting electrons around the nucleus (Taber, 2005). The latter was characterized by Taber (2005) as a deficiency learning impediment or as a fragmentation learning impediment depending on whether students' prior knowledge is absent or not. According to the former, students do not have the prerequisite knowledge/experience to explain the stability of atom in the planetary model or the circular motion as an accelerated motion due to centripetal force, whereas according to the latter, students cannot convey existing prior knowledge to contexts.

As for the students of Cluster 3, they seem to have a high probability to represent the atomic structure within the particle model independently of the task. For this small portion of students (7.24%) conceptual change on atomic structure appears difficult.

Remarkable are the results concerning the effect of students' ideas and misconceptions for the atom characteristics as identity and behavior on their portrayed representations of the atomic structure. These results indicate that the understanding of ontological features of atoms is crucial. A scientifically accepted portrayed representation of the atomic structure has as precondition the understanding of the atomic ontological characteristics. When such characteristics are not understandable, the atom is probably acquired as a particle in students' mind, with its structure to have no particular meaning. On the contrary, a thorough clarification of the atom characteristics during the teaching procedure gives more chances to students for a scientific portrayed representation of the atom.

As for the cohort characteristics (Figure 4), they seem to play an important role. Students with atomic portrayed representations within the Bohr's and quantum models increase dramatically within Lyceum classes along with the age. However, the best student performances corresponded to the 4th cohort ("science and math direction"), highlighting the importance of curriculum. Although, the 4th cohort includes students of the same age (comparing to the 3rd cohort), their performance was higher, probably due the detail approach of the curriculum to the atom ontological characteristics and the quantum model.

IMPLICATIONS FOR SCIENCE EDUCATION

The findings of the present study highlight that students' portrayed representations of the atomic structure are quite coherent, presenting a remarkable resistance to change in different contexts, but the effect of the students' knowledge of the atom ontological characteristic as identity and behavior and the cohort characteristics (i.e., the curriculum and the age) seem to affect significantly these representations.

Teaching procedure should acknowledge that, there is the student's coherent preference to more simple and concrete models over the more complex and abstract ones. For the lower grades, where Bohr's model is a desirable context for the description of the atomic structure, this advocates a teacher's effort to overcome the student tendency to "see" atomic structure through the simpler context of the nuclear model, by emphasizing the key differences between nuclear and Bohr's models. As for the upper grades, although the Bohr's model appears to be dominant, the present study provides evidence that there are significant possibilities to change the way students represent the atomic structure by the implementation of a suitable teaching context.

Such a teaching context should anticipate that, students' knowledge of the atom as identity and behavior appears to affect significantly any progress toward the acquisition of the quantum model. Thus, considering this finding, as well as suggestions indicating that students' knowledge has been found to be fragmented (Zarkadis et al., 2020), it seems that a possible root toward the acquisition of the quantum model could pass through the activation and the reconstruction of the appropriate pieces of knowledge dealing with key points of the quantum model (Zarkadis and Papageorgiou, 2020). It is essential, for example, to emphasize points highlighting concepts such as probability' or "quantization" of the energy of electrons, or to pay attention on differences between concepts such as "orbital" and "orbit." To this end, curriculum and textbooks should also support such an effort. Both should provide teachers with appropriate tools like lexical manipulations that facilitate such differences between concepts (Taber, 2005) and use of visualizations for the portrayed representations of the atomic structure (Kozma and Russell, 2005).

REFERENCES

Adbo, K., & Taber, K.S. (2009). Learners' mental models of the particle nature of matter: A study of 16-yearold Swedish science students. *International Journal of Science Education*, *31*(6), 757-786.

Adbo, K., & Taber, K.S. (2014). Developing an understanding of chemistry: A case study of one Swedish student's rich conceptualisation for making sense of upper secondary school chemistry. *International Journal of Science Education*, *36*(7), 1107-1136.

Allred, Z.D.R., & Bretz, S.L. (2019). University chemistry students' interpretations of multiple representations of the helium atom. *Chemistry Education Research and Practice*, *20*(2), 358-368.

Bakk, Z., Tekle, F.B., & Vermunt, J.K. (2013). Estimating the association between latent class membership and external variables using bias adjusted three-step approaches. *Sociological Methodology*, *43*, 272-311.

Bao, L., & Redish, E.F. (2006). Model analysis: Representing and assessing the dynamics of student learning. *Physical Review Special Topics Physics Education Research*, *2*(1), 010103.

Bartholomew, D.J., Knott, M., & Moustaki, I. (2011). *Latent Variable Models and Factor Analysis: A Unified Approach*. (3rd ed.). Hoboken, New Jersey: John Wiley.

Clogg, C.C. (1995). Latent class models. In G. Arminger, C.C. Clogg, & M.E. Sobel (Eds.), *Handbook of Statistical Modeling for the Social and Behavioral Sciences*. pp. 311-359. Plenum.

Science Education International
32(2), 164-171
https://doi.org/10.33828/sei.v32.i2.10

Cokelez, A. (2012). Junior high school students' ideas about the shape and size of the atom. *Research in Science Education*, *42*(4), 673-686.

Cokelez, A., & Dumon, A. (2005). Atom and molecule: Upper secondary school French students' representations in long-term memory. *Chemistry Education Research and Practice*, *6*(3), 119-135.

Derman, A., Koçak, N., & Eilks, I. (2019). Insights into components of prospective science teachers' mental models and their preferred visual representations of atoms. *Education Sciences*, *9*(2), 154.

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

diSessa, A.A., Gillespie N., & Esterly, J. (2004). Coherence versus fragmentation in the development of the concept of force. Cognitive Science, *28*, 843-900.

Eymur, G., Çetin, P., & Geban, O. (2013). Analysis of the alternative conceptions of preservice teachers and high school students concerning atomic size. *Journal of Chemical Education*, *90*(8), 976-980.

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

Griffiths, K.A., & Preston, R.K. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching*, *29*(6), 611-628.

Hammer, D. (1996). Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions? *Journal of the Learning Sciences*, *5*, 97-127.

Harrison, A.G., & Treagust, D.F. (1996). Secondary students'mental models of atoms and molecules: Implications for teaching chemistry. *Science Education*, *80*(5), 509-534.

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

Ioannides, C., & Vosniadou, S. (2002). The changing meanings of force. *Cognitive Science Quarterly*, *2*, 5-62.

Kalkanis, G., Hadzidaki, P., & Stavrou, D. (2003). An instructional model for a radical conceptual change towards quantum mechanics concepts. *Science Education*, *87*(2), 257-280.

Kikas, E. (2004). Teachers' conceptions and misconceptions concerning three natural phenomena. *Journal of Research in Science Teaching*, *41*(5), 432-448.

Kozma, R., & Russell, J. (2005). Students becoming chemists: Developing representational competence. In Gilbert, J.K., (Ed.), *Visualization in Science Education*. Berlin: Springer. pp. 121-145.

McCutcheon, A.L. (1987). *Latent Class Analysis.* Sage.

McKagan, S.B., Perkins, K.K., & Wieman, C.E. (2008). Why weshould teach the Bohr model and how to teach it effectively. *Physical Review Special Topics Physics Education Research*, *4*, 010103.

Nakiboglu, C. (2003). Instructional misconceptions of Turkish prospective chemistry teachers about orbitals and hybridization. *Chemistry Education Research and Practice*, *4*(2), 171-188.

Nicoll, G. (2001). A report of undergraduates' bonding misconceptions. *International Journal of Science Education*, *23*(7), 707-730.

Papageorgiou, G., Markos, A., & Zarkadis, N. (2016a). Students'representations of the atomic structure the effect of some individual differences in particular task contexts. *Chemistry Education Research and Practice*, *17*(1), 209-219.

Papageorgiou, G., Markos, A., & Zarkadis, N. (2016b). Misconceptions relating to ontological characteristics of the atom. Focusing on students' profiles. *Science Education International*, *27*(4), 464-488.

Papaphotis, G., & Tsaparlis, G. (2008). Conceptual versus algorithmic learning in high school chemistry: The case ofbasic quantum chemical concepts. Part 2. Students' common errors, misconceptions and difficulties in understanding. *Chemistry Education Research and Practice*, *9*(4), 332-340.

Park, E.J., & Light, G. (2009). Identifying atomic structure as athreshold concept: Student mental models and troublesomeness. *International Journal of Science Education*, *31*(2), 233-258.

Redish, E.F., & Smith, K.A. (2008). Looking beyond content: skill development for engineers. *Journal of Engineering Education, 97*(3), 295-307.

Stamovlasis, D., Papageorgiou, G., & Tsitsipis, G. (2013). The coherent versus fragmented knowledge hypotheses for the structure of matter: An investigation with a robust statistical methodology. *Chemistry Education Research and Practice*, *14*(4), 485-495.

Stamovlasis, D., Papageorgiou, G., Tsitsipis, G., Tsikalas, T., & Vaiopoulou, J. (2018). Illustration of step-wise latent class modelling with covariates and taxometric analysis in research probing children's mental models in learning sciences. *Frontiers in Psychology*, *9*, 532.

Straatemeier, M., van der Maas, H.L., & Jansen, B.R. (2008). Children's knowledge of the earth: A new methodological and statistical approach. *Journal of Experimental Child Psychology*, *100*(4), 276-296.

Taber K.S. (2002). Conceptualizing quanta illuminating the ground state of student understanding of atomic orbitals. *Chemistry Education Research and Practice*, *3*(2), 145-158.

Taber, K.S. (2003). The atom in the chemistry curriculum: Fundamental concept, teaching model or epistemological obstacle? *Foundations of Chemistry*, *5*(1), 43-84.

Taber, K.S. (2005). Learning quanta: Barriers to stimulating transitions in student understanding of orbital ideas. *Science Education*, *89*(1), 94-116.

Taber, K.S. (2008). Conceptual resources for learning science: Issues of transcience and grain-size in cognition and cognitive structure. *International Journal of Science Education*, *30*(8), 1027-1053.

Taber, K.S. (2013). Upper secondary students' understanding of the basic physical interactions in analogous atomic and solar systems. *Research in Science Education*, *43*(4), 1377-1406.

Taber, K.S., & García-Franco, A. (2010). Learning processes in chemistry: Drawing upon cognitive resources to learn about the particulate structure of matter. *Journal of the Learning Sciences*, *19*(1), 99-142.

Talanquer, V. (2009). On cognitive constraints and learning progressions: The case of "structure of matter". *International Journal of Science Education*, *31*(15), 2123-2136.

Talanquer, V. (2014). Threshold concepts in chemistry: The critical role of implicit schemas. *Journal of Chemical Education*, *92*(1), 3-9.

Tsaparlis, G., & Papaphotis, G. (2009). High-school students' conceptual difficulties and attempts at conceptual change: The case of basic quantum chemical concepts. *International Journal of Science Education*, *31*(7), 895-930.

Vaiopoulou, J., & Papageorgiou, G. (2018). Primary students' conceptions of the Earth: Re-examining a fundamental research hypothesis on mental models. *Preschool and Primary Education*, *6*(1), 23-34.

Vosniadou, S., & Brewer, W.F. (1994). Mental models of the day/ night cycle. *Cognitive Science*, *18*(1), 123-183.

Wang, C.Y., & 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. *Chemistry Education Research and Practice*, *14*(1), 130-146.

Zarkadis, N., & Papageorgiou, G. (2020). A fine-grained analysis of students' explanations based on their knowledge of the atomic structure. *International Journal of Science Education*, *42*(7), 1162-1182.

Zarkadis, N., Papageorgiou, G., & Stamovlasis, D. (2017). Studying the consistency between and within the student mental models for atomic structure. *Chemistry Education Research and Practice*, *18*(4), 893-902.

Zarkadis, N., Stamovlasis, D., & Papageorgiou, G. (2020). Students' ideas and misconceptions about for the atom: A latent class analysis with covariates. *International Journal of Physics and Chemistry Education*, *12*(3), 41-52.