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Student ideas and misconceptions for the atom: A Latent Class Analysis with covariates

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Abstract
The current study investigates students' fundamental ideas and misconceptions about ontological features of atoms identity and behaviour. These conceptions are being investigated across tasks with varying context. Participants were secondary education students in eighth, tenth and twelfth grades. Latent Class Analysis (LCA), a psychometric approach, was implemented to analyze a set of four tasks, in order to identify distinct mental models, which share specific sets of misconceptions. Furthermore, the detected mental models were associated with a number of external variables, such as the age, and the three cognitive variables: formal reasoning, field dependence-independence and divergent thinking. Results indicated that age and two cognitive variables under study had significant effects on students' mental models. Implications for theory and practice are discussed.

Keywords
atom, student misconceptions, cognitive variables, latent class analysis (LCA)

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Introduction
A plethora of studies in science education have highlighted that the scientific knowledge concerning the atom is insufficient for a wide range of students' ages and a number of various misconceptions exist. This insufficiency could referred to either, ontological features of atoms' identity and behavior or/and to its structure. In regards to the former, research evidence indicates that students often attribute macroscopic characteristics to atoms (Adbo & Taber 2009, 2014; Derman, Koçak & Eilks, 2019; Talanquer, 2009), they show inability to distinguish between atom and other submicroscopic particles, i.e., molecules or ions (Cokelez & Dumon 2005; Nicoll 2001; Papageorgiou, Markos & Zarkadis, 2016b), or they attribute animistic and anthropomorphic characteristics to atoms (Papageorgiou et al., 2016b; Taber & Adbo, 2013; Talanquer, 2013). However, looking from another perspective, studies targeting on the nature and the coherency of the relevant to the atom students' ideas and misconceptions are quite few. Evidence has indicated for instance, that students' mental models for the atomic structure are fragmented and that there is consistency, neither between nor within them (Zarkadis, Papageorgiou & Stamovlasis, 2017). On the contrary, there is no analogous evidence concerning students' ideas on the ontological features of atoms identity and behavior. In the present work, the coherence of such ontological features is investigated, taking also into account the effect of cognitive and developmental variables.

Theoretical background
Students' knowledge for the atom identity and behaviour
One the most common students' misconceptions concerning the particulate nature of substances is the attribution of macroscopic characteristics to submicroscopic entities (Griffiths & Preston, 1992; Harisson & Treagust, 1996; Adbo & Taber, 2009; Talanquer 2009, 2013; Derman et al. 2019). The case where the submicroscopic entity is the atom is often reported as *'inheritance assumption'* (Talanquer, 2009). According to this assumption, the atoms of a substance have the same properties with the properties of the substance. For instance, oxygen atoms are in gaseous state when iron atoms are in solid state, an atom of oxygen is lighter or softer compared to that of iron (Papageorgiou et al., 2016b) or atoms of a substance in the solid state cannot move (Adbo & Taber, 2009).

Focusing on the submicro-level, many students show a lack of distinction between atom and other submicroscopic particles, mostly molecules and ions. Atom and molecule are used the one instead of the other in a similar way according to the occasion or they are treated as synonyms (Nicoll, 2001; Cokelez & Dumon, 2005; Papageorgiou et al., 2016a). For instance, water molecules are reported to consist of hydrogen and oxygen molecules (Cokelez & Dumon, 2005) or 'molecule' and 'atom' are used interchangeably when explaining polarity (Nicoll, 2001). As a result the size of atoms is not very clear to students. Often the atom is reported, as being similar to a molecule, as a 'point of a needle' or a 'head of a pin' (Griffiths & Preston, 1992; Harrison & Treagust, 1996; Cokelez, 2012). In other occasions, students present the size of the atom as larger than that of a molecule (Griffiths & Preston, 1992) or believe that atoms and ions have the same size when they have the same number of protons (Eymur, Cetin, & Geban, 2013). Confusion also seems to exist between characteristics of the atom and those of the cell, attributing animistic and anthropomorphic characteristics to atoms considering them often as alive (Griffiths & Preston 1992; Harisson & Treagust, 1996; Cokelez, 2012; Papageorgiou et al., 2016a,b). For instance, students believe that atoms are made of cells (Cokelez, 2012), they are living particles with specific properties and biological functions (Harisson & Treagust, 1996), or they can feel,

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need, want, are happy getting a full octet etc. (Nicoll 2001; Taber 2003; Taber & Adbo, 2013). However, there are other cases, where students overestimate the atom over the other entities of the submicro-level, giving them an 'ontological priority' (Taber, 2003). This means, that they consider atoms as the only basic units of substances at the submicro-level, ignoring that 'molecules' and 'ions' are also fundamental entities and considering molecules as combinations of atoms and ions as altered atoms.

Coherency of mental models

Research in students' naïve knowledge is dominated by the assumption of coherency, where the misconceived knowledge appears to comprise of stable mental models or theory-like coherent mental structures; these structures are supposed to resist to conceptual change (Ioannides & Vosniadou, 2002; Vosniadou 2002). On the contrary, the 'fragmented knowledge' or 'knowledge in pieces' alternative perspective (diSessa, 1993; diSessa, Gillespie & Esterly, 2004) states that students mental models are formed by the combination of smaller cognitive units (pieces of knowledge) that are activated 'in situ' when a phenomenon or a situation should be explained. Conceding prepositions stated that students' mental models could be coherent or fragmented depending on the particular topic or the general context that is studied (Hammer, 1996). Contributions to the above theoretical debate have raised methodological issues, while cutting-edge statistical approaches have been proposed for detecting valid empirical evidences for coherency or fragmentation (Straatemeier, van der Maas & Jansen, 2008; Stamovlasis, Papageorgiou & Tsitsipis, 2013; Vaiopoulou, Stamovlasis & Papageorgiou, 2017; Vaiopoulou & Papageorgiou, 2018; Zarkadis et al., 2017). The application of Latent Class Analysis, LCA, an advanced psychometric modeling, has illuminated to a great extent the conflicts between fragmented versus coherent knowledge hypotheses. LCA is implemented in this paper in order to explore students' particular misconceptions, as parts of possibly coherent mental models, and examining potential associations with some individual differences.

Cognitive factors and students' ideas

At the interface between cognitive psychology and science education, research has demonstrated that among various psychometric factors, *Field Dependence/ Independence* (FDI), *Formal Reasoning* (FR) and *Divergence* (DIV) have been major predictors of student performance in understanding the particulate nature of matter (Stamovlasis & Papageorgiou 2012; Tsitsipis et al., 2012), as well as, that significant correlations exist between these variables and students' ideas for the characteristics of the atom or students' representations of the atomic structure (Papageorgiou et al., 2016a,b). Thus, it would be interesting to investigate the effect of these cognitive factors on the way in which students' ideas for the characteristics of the atom affect their mental models for the atomic structure.

The three psychological constructs, which belong to neo-Piagetian framework, can briefly be described as follows: *Formal Reasoning* (FR), refers to one's ability to use concrete and formal operational reasoning (Lawson, 1978). *Field Dependence/ Independence* (FDI) refers to the ability to identify relevant information from a complex context (Witkin *et al.*, 1971). *Divergence* (DIV) refers to ones' ability to find several equally acceptable solutions to a problem (Bahar, 1999).

Rationale and research questions

The aim of the present work is to explore students' particular misconceptions and to examine potential associations with some individual differences. The literature review presented in the previous section dictates the need for further research on this subject matter and particularly, the investigation of students' misconception as parts of potentially coherent mental structures. In order to attain this target, the proper methodological choices should be made. Taking into account the limitations of the traditional approaches related to distributional assumptions and linear relationships, the present research applies Latent Class Analysis (LCA), which is more appropriate for the case. LCA is a psychometric method, where a distinction between latent and observable variables is made and the latent construct is considered as the common cause of the observables - the responses to the relevant questionnaire/items (Bartholomew, Knott & Moustaki, 2011). In the present endeavor, both the observables (misconceptions) and the latent variables (coherent mental structures) are categorical. LCA is the appropriate tool to examine these latent and observable variables in tandem (Stamovlasis et al., 2013; 2018) and to investigate the type of misconceptions appearing under different task conditions testing a fundamental hypothesis concerning the degree of coherence of students' mental representations before they acquire the science view. Moreover, an attempt was made to explain the achieved level of comprehension by implementing psychological constructs from neo-Piagetian framework. In particular, the present study focuses on responding to the following research questions:

1. Do students' ideas and misconceptions for the atom about characteristics such as identity and behavior belong to a coherent mental structures?

2. How and to what extent are cognitive factors (i.e. formal reasoning, divergent thinking and field dependence/independence) and developmental factors such as age associated with students' relevant ideas and misconceptions?

Answering the above research questions will illuminate the nature of students' conceptions of the atom and their association with the role of cognitive factors.

Methodology

Sample and procedure

A total of 421 students (55.1% female) of the 8th (n=127, age 14), 10th (n=167, age 16) and 12th (n=127, age 18) grades of secondary schools from Northern Greece participated in the study. Students were from various socio-economic levels and attended mixed ability classes in regular public schools. Data were collected during the last semester of the school year by means of four paper-and-pencil tests. Students in each one of the grades had been taught the subjects before the study, using the same textbook and following the National Science Curriculum for Greece

(Greek Pedagogical Institute, 2003). The first test was designed to assess students' ideas of the atom characteristics, whereas the rest were the three psychometric tests for formal reasoning, field dependence/independence and divergent thinking, respectively.

Instruments

The present study is a part of a wider project aiming to access student understanding of sub-atomic world. Details and validity issues about the tests and the selected items can be found elsewhere (Papageorgiou et al., 2016a, b), whereas merely a brief presentation of them is provided here. Two marking schemes were applied. One in an ordinal scale, which used to provide reliability measures (Cronbach's alpha), and the second in a nominal scale identifying categories corresponding to distinct misconceptions or mental models, which are implemented in LCA analyses.

The test concerning the atom

The test was developed by the authors especially for the study. Four tasks relating to the characteristics of the atom as identity and behavior are included in the present work. In these tasks, students were asked to explain and/or justify the following:

- The differences, if any, when using the words 'atom', 'molecule' and 'ion', or is it about the same particle which is differently expressed occasionally (Task 1).
- Whether 'atoms' are/could be alive (Task 2).
- The differences, if any, between iron atoms in solid and liquid states (Task 3).
- The differences, if any, between oxygen atoms and iron atoms (Task 4).

The above four tasks gave an acceptable Cronbach's alpha reliability ($\alpha = 0.73$).

Students' answers were grouped in three categories, namely Category 'SciRe' which corresponds to scientifically accepted response, Category 'M' which corresponds to misconceptions, and Category 'NR' which corresponds to unclear or no response. Further, from a fine analysis of category M, six specific misconceptions were revealed and were coded as distinct categories, as follows:

M1: Particle-cell confusion (atoms as living organisms with relevant functions)

M2: No distinction between particles (atom, molecule, ion as synonyms)

M3: The atom as the only fundamental particle (ontological priority of atoms)

M4: The atom as a compact unit, unchangeable under any change

M5: Macroscopic characteristics are attributed to atoms or/and to sub-atomic particles

M6: The atoms have anthropomorphic characteristics

The tests concerning individual differences

Students' individual differences were assessed on the basis of the English versions of three cognitive tests, which were adapted and translated into Greek, whereas their original scoring system was maintained. In particular:

Formal Reasoning (FR): This ability was measured using the Lawson paper-and-pencil test (Lawson, 1978), which consisted of the 15 following items: conservation of mass (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 duration for its completion was 45 min. Cronbach's alpha reliability coefficient was found to be 0.77.

Field dependence/independence (FDI): It was measured using the Group Embedded Figures Test (Witkin, *et al.*, 1971), a twenty-item test in which students dissembled simple 'hidden' figures concealed within ones more complex (duration 20 min). A field dependent learner has lower scores whereas higher scores show a more field independent learner. Cronbach's alpha was found 0.84.

Divergent thinking (DIV): It was measured within 20 min using a six-item test designed by Bahar (1999), including: Generation of words with a similar meaning to those given (item 1), generation of up to four sentences using words in a form given (item 2), drawing of up to five sketches relevant to a given idea (item 3), writing of as many things that have a common trait as possible (item 4), writing of as many words as possible, that begin with one specific letter and end with another specific one (item 5) and listing of all ideas about a given topic (item 6). Cronbach's alpha was found 0.69.

Statistical Analysis-LCA

LCA is actually a model-based cluster analysis focuses on finding discrete groups of participants, which share similar response patterns, that is, on identifying latent classes corresponding to different students' mental representations on the matter under investigation. LCA has been proved efficient and robust methodology in research for mental models measuring their coherency via the consistency of students' responses. The respondents in a latent class are considered homogeneous with respect to model parameters that characterize their responses to the instrument used (McCutcheon, 1987). LCA implements Bayesian statistics in order to assign students to group membership based on a set of conditional probabilities (CP). CP is the probability of providing a certain pattern of responses given that the student belongs to a specific group. The latent class predictions are made via the posterior probability of belonging to a class given an observed response pattern y, $p(y|c)$, by applying Bayes's theorem:

$$P(c|y) = \frac{P(c|y) \times P(c)}{P(y)}$$

Where $p(y|c)$ is the conditional probability of y given c, and $p(c)$ and $p(y)$ are the probabilities of c and observed pattern y, respectively.

The classification procedure provides all mathematical cluster solutions from which the most fit is chosen by the researcher. The fit of a latent class model can be assessed by a number of indicators such as the number of parameters, entropy-R^2, likelihood ratio statistic (L^2), Bayesian Information Criterion (BIC), Akaike's Information Criterion (AIC), degrees of freedom and bootstrapped p-value (Vermunt & Magidson, 2002).

Moreover, analysis of covariates could be included in the model and determine the relationships between class memberships and external variables (Bakk, Tekle & Vermunt, 2013; Vermunt, 2010). In the present study the three-step LCA approach was used:

i) First, the underlying latent clusters were identified using the input variables;
ii) Second, the individuals were allocated to latent classes using the *modal* assignment approach, and
iii) The third step is the estimation of the effects of covariates along with the application maximum likelihood (ML) bias correction (see Bakk et al., 2013).

Results

LC Analysis

The LCA used the set of tasks (Tasks 1, 2, 3 and 4) as input and lead to a two-class solution (entropy $R^2 = 0.79$, $df = 396$, classification-error = 0.0829, BIC = 4077.45, $Npar = 32$, p=0.15) as the best parsimonious model with the lower BIC values (**Table 1**).

Table 1. LCA solutions and the model fit indexes (Input variables, Task 1, Task 2, Task 3 and Task 4).

	LL	BIC(LL)	Npar	L^2	df	p-value	Class. Err.	Entropy-R^2
1-Cluster	-2020.8	4126.20	14	4011.79	407	-	0	1
2-Cluster*	-1942.04	4077.45	32	3854.26	389	0.15	0.0829	0.79
3-Cluster	-1915.82	4133.76	50	3801.81	371	0.12	0.1839	0.72
4-Cluster	-1901.67	4214.23	68	3773.52	353	0.01	0.8350	0.64
5-Cluster	-1888.4	4296.46	86	3746.98	335	0.01	0.1868	0.56

Table 2 presents the two clusters with the corresponding conditional probabilities and along with Figures 1 and 2, showing the cumulative probabilities for each cluster respectively, exhibit the properties of those latent classes. Cluster 1 (60.10% of the sample) includes students with higher conditional probabilities in category *SciRe* for three out the four tasks (Tasks 2, 3 and 4). This cluster includes students, who have progressed towards scientifically accepted ideas, to some degree (**Figure 1**). Cluster 2 (39.90% of the sample) includes students with medium or low conditional probabilities distributed to all responses, including the categories 'M' of various misconceptions (**Figure 2**). In this cluster there is no prevailing response pattern along the set of tasks; the response pattern is inconsistent regarding the science view and/or the conveyed misconception (M1 to M6). That is, the hypothetical mental representations are incoherent (Stamovlasis, et al., 2013; Zarkadis et al. 2017; Vaiopoulou & Papageorgiou, 2018) - the science view and the detected misconception are alternated in the response patterns across tasks.

Table 2. The two clusters and the corresponding Conditional Probabilities (CPs), LCA

Categories per Task	CPs for Cluster 1 (Cluster Size 60.10%)	CPs for Cluster 2 (Cluster Size 39.90%)
Task 1		
NR	0.0164	0.1658
M1	0.7182	0.5614
M2	0.0952	0.053
SciView	0.1702	0.2199
Task 2		
NR	0.161	0.2933
M1	0.0979	0.1978
M5	0.0653	0.2231
M6	0.1632	0.1531
SciView	0.5127	0.1327
Task 3		
NR	0.043	0.2448
M4	0.0101	0.0205
M5	0.108	0.391
SciView	0.839	0.3437
Task 4		
NR	0.0571	0.3068
M3	0.1774	0.0245
M4	0.0654	0.1932
M5	0.0607	0.1347
SciView	0.6394	0.3407

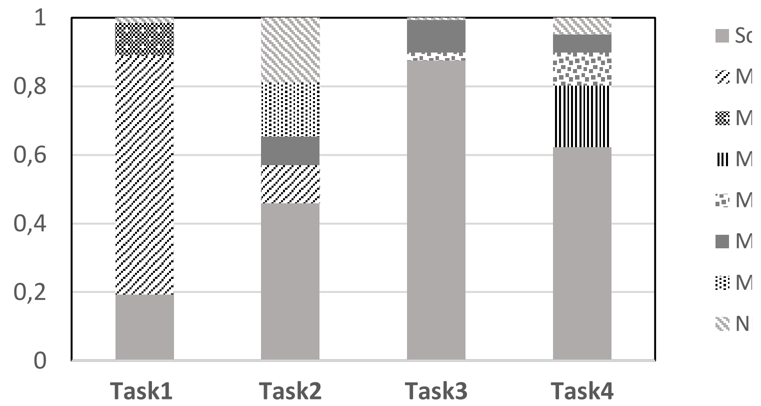

Figure 1. Conditional probabilities for Latent Class 1 (Cluster 1, 60.10%).

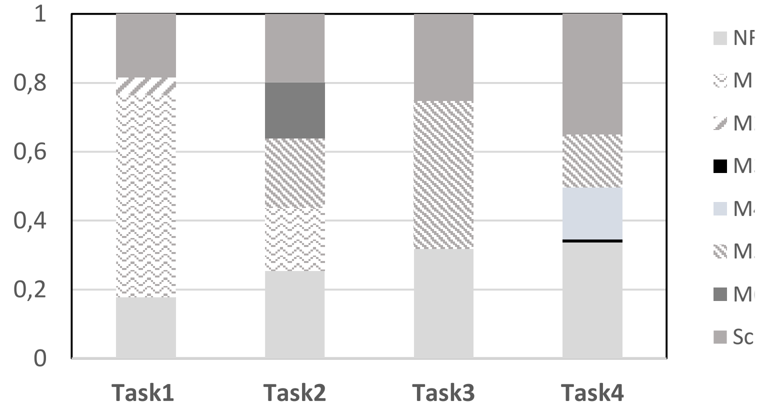

Figure 2. Conditional probabilities for Latent Class (Cluster 2, 39.90%)

Subsequently, the roles of cognitive variables and Age are investigated. **Table 3** shows the effects of the above covariates on cluster memberships. Formal Reasoning have a positive effect on Cluster 1 ($b = 0.1053$, $p<0.001$) along with the corresponding negative effect on Cluster 2. Field Dependence/Independence have also a positive effect on Cluster 1 ($b = 0.1026$, $p<0.001$) along with the corresponding negative effect on Cluster 2. The effect of Divergent Thinking on the cluster memberships appears to be statistically non-significant. For the *Age* which treated as categorical variable, age of eighteen has a positive effect on Cluster 1 ($b = 0.1360$, $p<0.001$), while negative effect appear for the ages sixteen ($b = -0.6694$, $p<0.001$) and fourteen ($b = -0.6911$, $p<0.001$). The corresponding effects of opposite signs appear for Cluster 2.

Table 3. Effects of Covariates on Class-memberships

Covariates	Cluster1	s.e.	*z*-value	Cluster2	s.e.	*z*-value	Wald	*p*-value
FR	0.1053	0.0160	6,.79	-0.1053	0.0160	-6.58	43.28	p<0.001
DIV	-0.0156	0.0175	-0.89	0.0156	0.0175	0.89	0.793	ns
FDI	0.1026	0.0381	2.69	-0.1026	0.0381	-2.69	7.25	p<0.01
Age								
14	-0.6911	0.1855	-3.73	0.6911	0.1855	3.73	16.75	p<0.001
16	-0.6694	0.2534	-2.64	0.6694	0.2534	2.64		
18	1.3605	0.3529	3.85	-1.3605	0.3529	-3.85		

Discussion

Studying Table 2 together with Figures 1 and 2, a first evaluation of students' ideas for the atom characteristics could be made. Cluster 1, generally presents high consistency in students' ideas across the tasks (especially in Tasks 2, 3 and 4). This is expected to a certain degree, since Cluster 1 (60.10% of the sample) represents students with high conditional probabilities in scientifically accepted responses, and the scientific-view mental model is consistent by definition. On the contrary, Cluster 2, which represents the 39.90% of the students, who retain misconceptions about the atom characteristics, shows an inconsistency across tasks. Among the six categories (M1 to M6) of misconceptions, M1, M4 and M5 present significant conditional probabilities in all tasks. That is, a student who has not acquired the scientific view yet, when considering atom characteristics as identity and behavior, it is quite possible to convey macroscopic characteristics to atoms or/and to sub-atomic particles (M5), to manipulate an atom as a compact unit, unchangeable under any change (M4) or to confuse the atom with the cell (M1), depending on the task context. However, the latter (M1) could be possible also for a student who has acquired the scientific view to a certain degree (see Cluster 1, Task 1). Students conflate characteristics, either between different levels of representation or within each level of representation, since they attribute macroscopic characteristics to atoms (Adbo & Taber 2009, 2014; Derman, Koçak & Eilks, 2019; Talanquer, 2009), they attribute animistic and anthropomorphic characteristics to atoms (Papageorgiou et al., 2016b; Taber & Adbo, 2013; Talanquer, 2013) or they confuse the atom with the cell, holding an *Atom-cell model* representation of the atom (Papageorgiou et al., 2016a; Zarkadis et al., 2017).

As for the effect of cognitive variables on students' ideas for the atom characteristics, when separately tested, Formal reasoning appears ones again to be a very significant predictor, along with FDI, while DIV was not associated with the cluster memberships. These finding is in line with other literature reports where the presence of FDI and DIV as predictors of students' performance in science education outcomes is not consistent (Danili & Reid, 2006). Their effects of course vary with the nature of the task, but often in multivariate analyses collinearity effect might exclude them from model specification. In addition, research has shown that FDI and DIV are associated with nonlinear effects, so their presence might be masked within linear modeling even though are theoretically expected to correlate with outcomes (Stamovlasis, 2010, 2011). The importance of FR is reinforced by the fact that it remains the main predictor when it is examined alone or concomitantly with other variables. The above findings have important implications for theory, research and educational practice.

Conclusions and implications for teaching and research

Since students' knowledge of the characteristics of the atom appears to be fragmented, science teachers' efforts should be focused, not only on the introduction of the appropriate pieces of knowledge dealing with such characteristics, but also on the way that students could organize productively and effectively these pieces. In order to do so, misconception categories M1 to M6 could be used as drivers. Taking them into account, teachers have to establish methodologies facilitating a certain context of atom identity and behavior, where atom characteristics are studied in contrast to both, macroscopic characteristics of the corresponding substances and characteristic of other microscopic (i.e., cell) and submicroscopic (i.e., molecules and ions) entities. Therefore, any teaching strategy should focus on helping students to realize the characteristics of each level of representation and how they are related to each other, in order to reduce possible students' tendencies to attribute irrelevant characteristics to the atom.

Of course, the introduction of the above context should be supported by the curriculum and appropriate textbooks. The curriculum, should also anticipate an introduction of the corresponding ideas compatibly with the age/grade, in order to eliminate the effect of Formal Reasoning in lower ages, whereas textbooks design should aim on the amelioration of FDI and DIV effects on students' comprehension about the atom characteristics. For instance, textual characteristics should help students to avoid possible focus on surface features that can lead them to hybrid mental models (Muniz et al., 2018) where atom characteristics coexist with others.

Furthermore, the implications for research are also important. These concern the implementation of a robust, person-centered methodological approach. Research in this area, is driven for decades by ideas considering the nature of children's knowledge as consisted by naïve but coherent (to some degree) entities, which for the contemporary measurement theory are categorical latent variable; thus the implementation of LCA is more appropriate contrary to other psychometric approaches e.g. factor models. Therefore, epistemologically, the degree of coherence in students' mental models is a better measure of their understanding science concepts comparing to the assessment via interval scales. Moreover, LCA provides the prospect to test theoretical issues on coherent vs fragmented knowledge hypotheses under various topics and circumstances.

Declaration of Conflict of Interests

The authors have no competing interests to declare.

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