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The effect of three cognitive variables on students' understanding of the particulate nature of matter and its changes of state

Abstract

In this study, students' understanding of the structure of matter and its changes of state, such as, melting, evaporation, boiling and condensation was investigated in relation to three cognitive variables: logical thinking, field-dependence/field-independence and convergence/divergence dimension. The study took place in Greece with the participation of 329 ninth-grade junior high school pupils (age 14-15). A stepwise multiple regression analysis revealed that all of the above mentioned cognitive variables were statistically significant predictors of the students' achievement. Among the three predictors, logical thinking was found to be the most dominant one. In addition, students' understanding of the structure of matter, along with the cognitive variables, were shown to have an effect on their understanding the changes of states and on their competence to interpret these physical changes. Path analyses were implemented to depict these effects. Moreover, a theoretical analysis is provided that associates logical thinking and cognitive styles with the nature of mental tasks involved when learning the material concerning the particulate nature of matter and its changes of state. Implications for science education are also discussed.

Keywords

Particulate structure of matter, changes of state, logical thinking, cognitive styles, field-dependence/field-independence, convergence/divergence thinking.

Introduction

This paper contributes to understanding the students' difficulties related to the structure of matter and its changes of state, by investigating the role of some cognitive variables. The structure of the present report has as following: First, in the Introduction section, a lucid review is presented in order to highlight the extent and the diversity of students' difficulties, and in addition to show the limitations and the partial success of the teaching interventions reported. Second, the section on cognitive variables reports on the three cognitive variables, which have been related to science education research. In the third section, the Rationale of the present study is developed and the research hypotheses are stated.

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Next follow the sections of Method, Additional Research Directions, the Statistical Analysis and Results. In the Interpretation of results and Discussion section, a theoretical analysis is provided that associates the cognitive variables with the nature of mental tasks involved when learning about structure of matter and its changes of state, while in the final section implications for science education are discussed.

A great deal of research has been conducted in order to shed light on students' ideas related to the structure of matter and its changes of state. For the last decades, all relevant papers have reported conceptual understanding difficulties in this field.

With regard to gas state, Novick and Nussbaum (1978), after clinically interviewing eighth grade pupils in Israel, found that "a significant portion of the sample failed to internalize important aspects of the particle model". As a matter of fact, although it was only the minority of the subjects that adopted a continuous model of matter, many of those pupils who had accepted the particle model showed that they had a problem in conceiving the notion of "empty space" among particles, especially in the gas state. Therefore, they erroneously responded by filling the space among gas- particles with other particles, such as air or dust. Moreover, the intrinsic motion of gas particles was also found to be a difficult concept. That was attributed to various causes, e.g. to low gravity or to the air moving the particles. In a later cross-age study, Novick and Nussbaum (1981) used a paper-and-pencil instrument in order to penetrate pupils' understanding regarding some aspects of the particle model associated mainly with gases. Their study involved subjects over a wide range of age, from fifth-grade pupils to university sophomores, and they found again a different internalization of the various aspects of the particle model. It is important that only 20% of the elementary-school pupils and the high-school juniors as well, answered that there is no material between the particles. The corresponding percentage at senior high school and university level increased only to 37%, indicating that the difficulty in conceiving the vacuum between particles is still persistent in higher education levels.

Another cross-age study investigating students' preconceptions of the nature of gases was conducted by Benson, Wittrock and Baur (1993), who reported a relatively limited number of misconceptions inferred from students' drawings. These misconceptions were found to be one or more of the following: (a) air is a continuous substance, (b) gas behavior is similar to liquid behavior and (c) there is relatively little space between gas particles. The authors underlined "the number of drawings that gave evidence of particulate views ranged from 8% for grades 2-4 to 85% for university chemistry students. However, 33% of the

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2 university students' drawings showed highly packed particles and only 37% showed particles
3 in an approximately correct geometrical distribution".
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5 Additional evidence for the inherent difficulty in conceiving the structure of the gas
6 state was reported by Stavy (1998), who argued that students do not develop spontaneously a
7 general idea of *gas* prior to their formal introduction on this matter. Definitions for the term
8 *gas* by means of the particulate theory of matter were given only by grade-8 and grade-9
9 students who had been taught this theory one or two years earlier, when they were in the
10 seventh grade. These definitions included one or more of the following points: distance
11 between particles, motion of particles, arrangement of particles and attraction forces between
12 particles. None of the seventh-grade students gave a definition at this level. In the light of the
13 above findings, one could conclude that a considerable time period might be required for the
14 assimilation of these ideas.
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20 With regard to solid and liquid states, students' conceptions were found to be similar
21 to those of gases: continuous or particulate model of matter, space between particles, particle
22 motion, attractions between particles (Renstrom et al., 1990; Lee et al., 1993; Johnson,
23 1998a). The adoption of the particle concept is not always in accordance with the scientific
24 view. Research has shown that students consider molecules as being in a continuous
25 substance like "blueberries in a muffin" (Lee et al., 1993). According to this view, "particles
26 are additional to the substance" (Johnson, 1998a).
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30 An additional and interesting point is that, students have a great deal of difficulty to
31 understand that the properties of the states of matter are due to the collective behavior of
32 particles. They often regard a particle or a molecule as a little quantity of a substance having
33 all the macroscopic properties of the substance. That is, ice molecules or particles are
34 regarded as frozen or 'solid molecules, water molecules as 'liquid molecules', and so forth
35 (Lee et al., 1993; Johnson, 1998a). Furthermore, molecules are described to undergo "the
36 same changes as the visible changes in the substances. Thus, molecules start to move when
37 ice melts into water, molecules of water are heated up and make water boil, or molecules
38 expand, contract, melt, evaporate, condense, and so forth" (Lee et al., 1993).
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43 Significant conceptual difficulties are reflected in the way that students make a
44 distinction between states, which are not always clear or complete. Secondary students'
45 misconceptions about liquids are due to the fact that they consider liquids to be merely in an
46 intermediate state between solids and gases. In this context, students overestimate the
47 molecular spacing in liquids. Furthermore, many of them believed that although particles in
48 gas and liquid state were in constant motion, there was no particle movement in solid state
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2 (Dow et al., 1978). In another study, molecular spacing in gases has been found
3 underestimated, while the particle motion has been ignored by the majority of the students
4 (Pereira & Pestana, 1991). Misconceptions have been also reported in relation to particle size
5 of a substance that is thought to vary in different states (Dow et al., 1978; Griffiths & Preston,
6 1989; Pereira & Pestana, 1991).
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10 In an attempt to further investigate the various students' conceptions related to the
11 nature of matter and organize them into conceptual categories, a longitudinal study with
12 secondary English pupils (ages 11-14) carried out by Johnson (1998a), led to the formation of
13 distinct models for students' classification on the strength of their particle thinking. These
14 distinct models are defined below:
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17 (1) *Model X*: Continuous substance. Particle ideas have no meaning. (2) *Model A*:
18 Particles *in* the continuous substance. The particles are additional to the substance. (3) *Model*
19 *B*: Particles *are* the substance, but with *macroscopic* character. There is nothing between the
20 particles. Individual particles are seen as being of the same quality as the macroscopic sample
21 - literally small bits of it. (4) *Model C*: Particles *are* the substance. The properties of a state
22 are seen as *collective* properties of the particles.
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26 In addition to the above, there are intermediate models. It was also suggested that these
27 models might represent stages through which, students' ideas evolve towards the science
28 model (Johnson, 1998a).
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31 As far as the changes of state are concerned, Osborne and Cosgrove (1983) investigated
32 students' perceptions by interviewing forty-three school pupils ranging in age from eight to
33 seventeen years. The findings were consolidated by means of a paper-pencil survey technique.
34 Regarding melting, in a question asking what is happening to a block of ice melting on a
35 teaspoon, only eight out of forty-three pupils answered in terms of the particulate structure of
36 matter. These pupils responded that the heat made the particles move farther apart. It appears
37 that the pupils used a general model, which relates volume and temperature for many
38 substances. Other common answers were: (a) ice melted because it was above its melting
39 temperature and (b) it just melted and changed into water. Regarding boiling, in the same
40 study, and in a question asking what the bubbles in boiling water were made of, only five out
41 of forty-three pupils (ranging from thirteen to seventeen years old) answered that the bubbles
42 consisted of steam. Common misconceptions in pupils' views were: (a) the bubbles were
43 made of heat, (b) the bubbles were made of air and (c) the bubbles were oxygen and
44 hydrogen. View (b) was the most frequent one, while view (c) was held by some older pupils.
45 Findings similar to (b) and (c) were also reported in a study of Bonder (1991).
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2 Bar and Travis (1991) made an effort to “widen the conclusions of Osborne and
3 Cosgrove concerning the application of abstract concepts by pointing out the universality of
4 their results in the course of extending them to another country” (p. 364). According to Bar
5 and Travis, “many children know that water changes into gas by the process of boiling, but
6 they do not understand that the same change can occur by evaporation” (p. 371). Thus, one of
7 their main new findings was that “the understanding of boiling precedes the understanding of
8 evaporation”.

9
10 During his longitudinal study, Johnson (1998b) explored, among others, the development
11 of children’s conceptions about boiling water. He ascertained that by the end of the study, half
12 of the pupils interviewed had reached the idea of the bubbles being “water as a gas” and that
13 this progress was facilitated by particle ideas. Having accepted these basic ideas, pupils are
14 able to develop a meaningful conception of what a gas is. Johnson considers that “the particle
15 model must be seen as a mean of first establishing the possibility of a sample of substance
16 being in a gas state” (p. 582).

17
18 Regarding the nature of steam above boiling water, in the study of Osborne and
19 Cosgrove (1983), the most common answers of pupils were: “smoke”, “water”, “a kind like
20 water” or “water in a different form”. Many children considered that steam had changed into
21 air while some others thought that the air and the steam were the same. Also, there were
22 pupils who thought that the steam was made of oxygen and hydrogen. Expectedly, some of
23 these answers are similar to those describing the bubbles in boiling water. The same authors,
24 in order to further investigate children’s views about condensation from steam, placed a
25 saucer (plate) above boiling water and then asked children about the water that had been
26 formed on the saucer’s surface. The questions were: “What is this on the saucer?” and “What
27 has happened here?” Only seven out of forty-three pupils responded in such a way that
28 involved a particle model. The most characteristic of pupils’ responses were: (a) it has all
29 gone sweaty, (b) the steam makes the plate wet, (c) the steam changes back into water, (d) the
30 hydrogen and oxygen in the steam recombine to form water and (e) the steam has cooled and
31 the water molecules have moved closer together. A noticeable fact is that although many
32 children used the term “condensation” to describe what had happened on the saucer, the
33 majority of them showed little real understanding of this term.

34
35 In order to elicit pupils’ views about evaporation, in the same study, the authors turned
36 the saucer upside-down so that the water from the condensation of the steam to be on the
37 upper side. After a while the water had evaporated. Pupils were asked what had happened to
38 the water. Although many of them replied using the word “evaporation”, again only few
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2 showed to have a scientifically deeper understanding of what this term means. The most
3 characteristic pupils' responses were the following: (a) it has gone into the plate; (b) it has just
4 gone...it has dried up; (c) it goes into the air and comes back as rain and (d) it changes into
5 air. Among the pupils who gave the answer (c), only eight included particles or molecules in
6 their explanations.
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9 Pupils' ideas on evaporation has been also investigated by Bar and Galili (1994), who
10 found that pupils' conceptual change on evaporation is correlated with pupils' cognitive
11 development, their conception of the conservation of matter and the adoption of an abstract
12 model of air. Johnson (1998c) has exemplified that there is a high consistency between
13 pupils' responses to phenomena, such as evaporation, condensation and boiling, and the
14 understanding of the nature of the gas state. The sound understanding of the nature of the gas
15 state in terms of the particle theory of matter constitutes an underlying background for the
16 understanding of all the above-mentioned changes of state. Particularly, for evaporation and
17 condensation, Johnson (1998c) has stated that until one understands them both, "it could be
18 argued that one really understands neither".
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21 Stavy (1990a) explored pupils' conceptions regarding conservation of matter during
22 evaporation or sublimation. In this study, pupils appeared to believe that "gas has no weight
23 or that gas is lighter than the same material in its liquid or solid state". Furthermore, according
24 to Stavy (1990b), "students believe that a molten material weights less than the same material
25 in its solid form and that gas weights less than the same substance in its liquid or solid form".
26 Similarly, Lee et al. (1993) found that students were confused about conservation of matter
27 during evaporation, boiling and condensation, as all these changes of state involve invisible
28 gases. "Since a substance becomes invisible during evaporation, some students thought that
29 the substance disappears and ceases to exist". To a lesser extent, though, students were also
30 found to have been "confused about the conservation of matter during melting and freezing"
31 as they considered that "ice is heavier than water" or that "ice has more stuff in than water".
32 Finally, Hatzinikita and Koulaidis (1997) exploring both the qualitative and quantitative
33 dimensions of pupils' ideas relevant to conservation of matter during evaporation, boiling and
34 condensation found that qualitative understanding precedes quantitative.
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36
37 In the light of various findings, such as those mentioned above, teaching interventions
38 have been conducted in order to promote students' conceptual understanding. Lee et al.
39 (1993) studied the performance of two sixth-grade groups of pupils that had been taught the
40 same science course concerning the nature of matter and its physical changes. Any valuable
41 information about conceptual barriers that had been acquired from the teaching process in the
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2 first group (1st year) was used to improve the teaching intervention in the second one (2nd
3 year). The study showed that the pupils of the second group performed better than those of the
4 first one. Conceptual and understanding difficulties in the second group were overcome to a
5 certain extent; however, by no means were they eradicated. Similarly, in an intervention study
6 (Author 3 et al., 2005) taken place in a Greek school in the fifth-grade, pupils in the
7 experimental group where particle ideas were incorporated in the teaching scheme, seemed to
8 have developed a better understanding of phenomena, such as, changes of state and mixing
9 compared to their peers in the control group. The results are promising and suggest that there
10 might be room for improvement.

11
12 In order to contribute to a further clarification of pupils' particle ideas and to facilitate
13 their better understanding regarding the changes of state, Author 3 et al. (2007) applied
14 thoroughly designed computer simulations in a teaching intervention and compared the results
15 to those of a corresponding intervention without the use of the software. In both, control and
16 experimental interventions, the concepts of the particle theory of matter were implemented.
17 The study showed that computer simulations seem to facilitate understanding of particle ideas
18 and physical changes, such as, melting and evaporation. However, there were again a
19 considerable number of pupils who did not reach the desired level of understanding.

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21 In another study, Tsai (1999) examined the effectiveness of an analogy activity specially
22 designed to overcome misconceptions of eighth-grade Taiwanese pupils about the
23 microscopic views of phase change. The control group was instructed through traditional
24 teaching and the results indicated that although the pupils of both groups improved their
25 performance in an immediate post-test, the retention was higher in the experimental group.
26 However, significant difficulties were not overcome, even though an improvement was
27 demonstrated.

28
29 Costu et al. (2007) attempted to facilitate students' conceptual change on boiling by
30 implementing appropriately designed teaching activities. The authors worked with fifty-two
31 university students enrolled in introductory chemistry courses. The results showed that the
32 teaching strategy followed "was an effective means of reducing the number of alternative
33 conceptions students held about the boiling concept" (p. 531). However, it was found that
34 "some students maintained their alternative conceptions throughout the study" (p.533), for
35 example, although "the students' belief that bubbles in boiling water contain air decreased
36 from pre-test (27%) to post-test (23%)", finally this belief increased considerably (47%) in a
37 retention post-test.

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It is worth mentioning here that a presupposition that might make the topic easier is basic knowledge of kinetic theory. However, in the related literature there is no explicit reference to *kinetic theory*, but some elements are incorporated in the particle theory of matter and specifically in the part that deals with gasses.

By all accounts, the findings from teaching interventions reinforce the evidence that despite the progress that could be achieved by means of appropriate teaching methods, pupils' misunderstandings of the particle nature and the physical changes of matter seem to persist to a considerable extent. Thus, the question raised is what hinders pupils' understanding. Researches investigating this question were focused on difficulties originated from the material itself and suggest some presuppositions for understanding the particle nature and the physical changes of matter. For instance, Johnson (1998a, b, c,) proposed more elementary dimensions, as presuppositions, namely the particulate and collective dimensions, which were elaborated in the introduction section and have also been examined in the present research.

However, the partially successful teaching and the fact that a number of students can approach the science view, while many others are far behind, suggest that the individual differences, which are ignored in the related research might be worth examining. Ergo, it could be a potential area of investigations. Considering the above, the present work attempts to shed light on students' misunderstandings in the field of the particulate nature of matter as well as its changes of state by taking into account their individual differences. Cognitive variables, such as field dependence/field independence, convergence/divergence dimension and logical thinking (for developmental level) are implemented in a quantitative research to explain the variation of students' *understanding* in this specific domain. The significance and the role of the above mentioned three cognitive variables in science education research are presented and elaborated in the following part.

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Cognitive variables

a. Field dependence/independence (FDI)

Field dependence/independence (FDI) is a cognitive style associated with one's ability to disembed relevant information from complex and potentially confusing contexts (Witkin et al., 1977). Long-lasting investigation on the matter showed that some people are dominated by any strong frame of reference or pattern in a stimulus field to such an *extent* that they have trouble in perceiving elements that cut across the pattern. Those who can insufficiently separate an item from its context and who readily accept the dominating field or context are

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2 characterized as field-dependent, while those who can easily “break up” an organized
3 perceptual field and separate readily an item from its context are characterized as field-
4 independent (Witkin & Goodenough, 1981). However, the two qualities are not regarded as
5 two distinct categories. On the contrary, there is a continuum between them and those of an
6 intermediate ability are classed as field-intermediate. The FDI cognitive style is also
7 connected with one’s ability to efficiently separate the *signal* from the *noise*. As *signal* could
8 be considered what matters or the significant information, while as *noise* the incidental,
9 peripheral and irrelevant information (Johnstone & Al-Naeme, 1991). Field dependence/
10 independence has been related to the information processing models as a moderator variable.
11 Field-dependent subjects appear to possess lower information processing ability, since part of
12 their capacity is being used to process irrelevant information (Johnstone & Al-Naeme, 1991;
13 Tsaparlis & Agelopoulos, 2001; Author 2, 2006).

14
15 Disembedding ability has been found to be related to structural ability in such a way
16 that field-independent individuals are more able to deal with ill-structured tasks than field-
17 dependent individuals (Goodenough & Karp, 1961; Witkin et al., 1962). In general, evidence
18 supports supremacy of field-independent learners regarding cognitive analysis and
19 restructuring skills in comparison with field-dependent learners (Witkin & Goodenough,
20 1981). Furthermore, academic performance in various disciplines such as language,
21 mathematics, natural sciences, social sciences, art and computer sciences was examined in
22 relation to FDI, leading to the conclusion that “in general field-independent subjects perform
23 better than field-dependent subjects, whether assessment is of specific disciplines or across
24 the board” (Tinajero & Paramo, 1998). Following, many research findings were in accordance
25 with the above conclusion (Bahar & Hansell, 2000; Danili & Reid, 2004; Kang et al., 2005;
26 Tsaparlis, 2005; Danili & Reid, 2006).

37 38 39 *b. Convergence / divergence (CD)*

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41 Convergence/divergence is another cognitive style that was introduced because of the
42 growing feeling that typical intelligence tests did not measure all aspects of intelligence.
43 Intelligence tests are thought to favor those who find the one conventionally accepted solution
44 to a problem when this solution is clearly obtainable from the information available. On the
45 other hand, those who are able to respond successively in problems requiring the generation
46 of several equally acceptable solutions obtain low scores in intelligence tests. The first are
47 described as convergers, while the second as divergers. Thus, convergent is thought to be
48 someone who focuses down-converges-on the one right answer in order to find the solution of
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2 a problem, while divergent is one who is capable to generate responses, to invent new ones, to
3 explore and expand ideas, and in a word, to diverge. Convergents use close reasoning, while
4 divergers show fluency and flexibility (Child & Smithers, 1973).

5
6 Getzels & Jackson (1962) distinguished intelligence from creativity. In the same
7 direction, Hudson (1966, 1968) tried to measure science/arts aptitude by devising different
8 types of tests and he was led to the conclusion that a converger “is substantially better at the
9 intelligent tests than he is at the open-ended tests; the diverger is the reverse” (Hudson, 1966).
10 Although many researchers adopted the equation of divergent thinking with creativity and
11 convergent thinking with intelligence, there were others that supported different results
12 (Nuttall, 1972; Bennett, 1973; Runco, 1986; Fryer, 1996).

13
14 In a Hudson’s (1966) research it was found that most of the physical scientists of his
15 sample were convergers while most of the art specialists were divergers. However, biology,
16 geography, economics, and general arts were found to have attracted “convergents and
17 divergers in roughly equal proportions” (Hudson, 1966). Regarding biology, Orton (1992) and
18 Bahar’s (1999) findings are consistent with Hudson’s finding. Other researches dealing with
19 the matter of the relationship between convergence/divergence cognitive style and
20 performance in science present interesting results: Divergent students were found to have
21 scored higher than convergent students in mini projects in chemistry (Al-Naeme, 1991).
22 Furthermore, divergers are reported to have achieved better results than convergers at the end
23 of a university science course, despite the fact that the majority of the students were
24 convergers (Field & Poole, 1970). Hudson (1966) noted on the matter that the convergers
25 tended to choose the sciences, but the divergers who did choose the sciences performed very
26 well. Johnstone & Al-Naeme (1995) reported that among the secondary pupils who
27 participated in mini-projects (problem solving at the bench), the curious, field-independent
28 and divergent pupils were those who did best. Danili and Reid (2006) explored high school
29 pupils’ performance in chemistry in relation to different assessment formats. The results
30 showed that the convergence/divergence cognitive style was correlated with pupils’
31 performance. The authors suggested that short answer or open-ended questions favored
32 divergent style pupils.

33
34 Moreover, research concerning high ability studies has suggested that creativity is a
35 **consistent** outcome of divergent thinking ability. Measures of divergent thinking have been
36 correlated with creative output in many different domains studied, such as, visual art,
37 literature, music, science, engineering, and business ventures (Guastello, Bzdawaka,
38 Guastello, & Rieke, 1992). Nevertheless, it is important to emphasize that the conceptual

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2 differentiation of convergent vs divergent thinking does not correspond to two contradictory
3 opposites. They are not mutually exclusive, but they are rather complementary and for science
4 education mixed types are required. For example, in a complex problem-solving process,
5 primarily, divergent abilities are necessary and later on in the process, convergent thinking is
6 required for decision-making and conclusion (Facaoaru, 1985; Heller, 2007).
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10 11 12 *c. Logical thinking (LTh)* 13

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15 Logical thinking is a Piagetian concept and refers to the ability of the subject to use
16 concrete- and formal-operational reasoning (Lawson, 1978, 1985, 1993). Concrete- and
17 formal-operational reasoning are needed for understanding of concrete- and formal-
18 operational concepts respectively. “Concrete-operational concepts are concepts whose
19 meaning can be developed from first hand experience with objects or events” while “formal
20 operational concepts are concepts whose meaning is derived through position within a
21 postulatory-deductive system”. “The term *postulatory-deductive* refers to the theoretical
22 models (systems) of science. Meaning is given to these concepts not through senses but
23 through imagination or through their logical relationship with the system” (Lawson, 1975).
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29 Logical thinking was assessed by the Lawson test, a pencil-paper test of formal
30 reasoning (Lawson, 1978). **The items included** in the test require the following reasoning
31 modes: Proportional, combinational and probabilistic reasoning as well as reasoning related to
32 the isolation and control of variables, conservation of weight and displaced volume. The first
33 four modes correspond to formal operational-reasoning, while the last two modes correspond
34 to late concrete- and early formal-operational reasoning (Lawson, 1978). There are a lot of
35 studies reporting that logical thinking plays a major role in students’ performance in science.
36 Some of them are of the following researchers: Sayre & Ball (1975), Lawson (1982),
37 Chiappeta & Russell (1982), Chandran et al. (1987), Lawson & Thomson (1988), Zeitoun
38 (1989), Niaz (1996), BouJaoude et al. (2004), Author 2 et al. (2005). It is worth mentioning
39 that in Lawson’s (1982) study, students’ formal reasoning has been correlated not only with
40 achievement in science and mathematics, but with social studies achievement as well.
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48 **Rationale - Research hypotheses**

49 All research work on understanding the particle nature and the physical changes of
50 matter has been mainly exploratory and descriptive by revealing students’ errors and
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2 misconceptions or difficulties without, however, providing explanations about their origin or
3 correlating them with independent variables. An exception is Johnson's work (1998a, b, c,)
4 where, the *particulate* and the *collective* dimensions were proposed as underlying
5 presuppositions for understanding the particle nature of matter. On the other hand, teaching
6 interventions showed that the difficulties still persist. Ergo, it is reasonable to hypothesize that
7 the area of investigation could fruitfully expand to individual differences and specifically to
8 cognitive variables, which have been proved predictive elsewhere in science education
9 research.

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14 When it comes to investigation of students' achievement in science with regard to
15 cognitive variables, there are only a few such cognitive variables that are taken into account
16 according to the literature, and these are the following: logical thinking (formal reasoning
17 ability), field-dependence/independence, convergence/divergence, prior knowledge, *M*-
18 capacity and working memory capacity (Lawson, 1983; Chandran et al., 1987; Zeitoun, 1989;
19 Johnstone & Al-Naeme, 1995; Niaz, 1996; Tsaparlis & Angelopoulos, 2000; Kang et al.,
20 2005).

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24 From the above variables, the prior knowledge and the information processing capacity
25 were not examined in this investigation. The influence of prior knowledge on students'
26 achievement is investigated when a teaching intervention is conducted and the comparison of
27 pre and post results is desired, which is not the case in this study. Moreover, *M*-capacity and
28 working memory capacity are associated with information processing and thus, they were
29 found to be mainly correlated with students' ability in solving problems (Niaz, 1996; Author
30 2 et al., 2005). However, in cognitive tasks with not a high processing demand these
31 variables might be expected not to play a major role (Lawson, 1983; Tsaparlis &
32 Angelopoulos, 2000). Regarding the present research, the instrument, which was implemented
33 for assessing students' understanding of science concepts and phenomena, did not require
34 simultaneous processing of a large number of *chunks* (Simon, 1974), that is, a large number of
35 specific facts or concepts. Therefore, students' working memory capacity (or *M*-capacity) was
36 not expected to constrain their performance. Consequently, the above variables were not
37 included in this study. However, it is worth mentioning that the information-processing
38 capacity might have shown positive correlation coefficients with achievements, because it is
39 correlated with the general IQ.

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48 The other three cognitive variables, logical thinking, field-dependence/independence
49 and convergence/divergence, seem to play a significant role in a wide range of tasks and they
50 affect students' performance in science according to the evidences mentioned in the previous
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1
2 section. Thus, these cognitive variables might also be potential predictors of students'
3 understanding the particulate nature of matter and its physical changes, such as melting,
4 evaporation, boiling and condensation. Moreover, aspects of the cognitive skills that are
5 behind the psychometric measurements of these variables could support their choice. For
6 instance, linguistic ability or disembedding ability might relate to the nature of mental tasks
7 involved when learning/teaching this specific domain material. These aspects are elaborated
8 *post factum*, in the discussion section, where a theoretical explanation of the findings is
9 provided.
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14 Considering the above, the main hypothesis in this research study is that students'
15 understanding of the particulate nature of matter and its changes of state are affected by the
16 following three cognitive variables: (a) logical thinking, (b) field-dependence/independence
17 and (c) convergence/divergence. In addition, the following hypothesis is tested: students'
18 understanding of the structure of matter along with the cognitive variables have an effect on
19 their understanding and explaining the changes of states. This second hypothesis along with
20 some additional research directions is further elaborated in a following section.
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25 **Method**

26 ***Subjects***

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28 This study was conducted with the participation of 329 ninth-grade junior high school
29 Greek pupils (age 14-15), 160 of which were male and 169 female. The sample consisted of
30 all the pupils of 18 classes each of which belonged to a different junior high school. All of the
31 schools are located in the prefecture of Fthiotida, in central Greece; 7 of them are in the
32 capital (Lamia) while the other 11 are dispersed at the municipalities of the prefecture. All of
33 the junior high schools of the capital and almost half of the remaining junior high schools in
34 the prefecture took part in the research. Pupils of different socioeconomic status and living
35 conditions comprised the sample.
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41 ***Instruments***

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43 Data were collected during one school year through paper-and-pencil tests. The
44 instruments used were the following:
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48 *Field dependence/independence (FDI)*: FDI ability of the subjects was assessed by a version
49 of the Wittkin et al. (1971) Group Embedded Figures Test (GEFT). This is a timed test (20
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2 min) in which the subject's task was to locate and outline simple figures concealed in
3 complex ones. In this study a Cronbach's alpha reliability coefficient of 0.84 was obtained.
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5
6 *Convergence/divergence (CD)*: A six-item test was used to measure the extent of divergency
7 of the subjects. Each item substantially constituted a mini test from itself. Briefly, the six
8 mini-tests asked students to do the following: (test-1) to generate words of the same or similar
9 meaning to those given, (test-2) to construct as many sentences as possible using four given
10 specific words in each sentence, the words to be used in the form as given, (test-3) to draw up
11 to five different figures relevant to the idea of a given word, (test-4) to write as many things as
12 possible that have a common trait, e.g. things that are round or that are round more often than
13 any other shape, (test-5) to think and write as many words as they could that begin with one
14 given letter and end with another given letter, (test-6) to list all of the ideas they could about a
15 given topic, whether or not it seemed important to them. The whole test had been widely used
16 by Bahar (1999). It had also been used by Danili and Reid (2006) for measuring divergency of
17 a Greek student sample. For the measures in this study, the Cronbach's alpha reliability
18 coefficient of the instrument is 0.76.
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27 *Logical thinking (LTh)*: Pupils' logical thinking abilities were measured using the Lawson
28 paper-and-pencil test of formal reasoning (Lawson, 1978). The test consists of 15 items
29 involving the following: conservation of weight (1 item), displaced volume (1 item), control
30 of variables (4 items), proportional reasoning (4 items), combinational reasoning (2 items)
31 and probabilistic reasoning (3 items). The students had to justify their answers. A Cronbach's
32 alpha reliability coefficient of 0.79 was obtained for the present sample.
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37 *Pupils' achievement, concerning their understanding of the particulate nature of matter and*
38 *its changes of state:*
39

40 The instrument was synthesized by selected items/questions, which have been used to access
41 students' knowledge on this specific domain in a number of research studies (Johnson, 1998a,
42 b, c; Osborne, & Cosgrove, 1983; Author 3, Author 2 *et al.*, 2008). In particular, it was
43 especially based on an extended and more elaborated version of the instrument used by
44 Author 3, Author 2 *et al.*, (2008).
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48 The test consists of 3 parts covering the following topics: the particulate nature of matter (first
49 part), the properties of a state as a result of the collective behavior of particles (second part)
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2 and the changes of state: melting, boiling, evaporation and condensation (third part). A brief
3 description of all the parts and their items follows:
4

5 Part 1: (The particulate nature of matter)

6 The first 3 items (1A, 1B, and 1C) concern the solid state.
7

8 1.A. Pupils are asked to choose among five alternatives (See Appendix), the figure that best
9 represents what they would “see” if they observed a sugar grain using a hypothetical
10 magnifying glass enabling the view of the grain structure.
11

12 1.B. Pupils are asked to explain what they think exists between molecules, in case they chose
13 a figure depicting molecules. Otherwise, they do not have to answer this question.
14

15 1.C. Pupils are asked to answer whether or not they think that the view of the sugar structure
16 through the hypothetical magnifying glass would remain “frozen” as the time is passing. They
17 are also asked to explain or justify their answers.
18

19 The following 3 items (2A, 2B, and 2C) concern the liquid state.
20

21 2.A. Pupils are asked to choose among five alternatives (See Appendix), the figure that best
22 represents what they would “see” if they observed a drop of pure (liquid) water using a
23 hypothetical magnifying glass enabling the view of the structure of the drop.
24

25 2.B. Pupils are asked to explain what they think exists between molecules, in case they chose
26 a figure depicting molecules. Otherwise, they do not have to answer this question.
27

28 2.C. Pupils are asked to answer whether or not they think that the view of the water structure
29 through the hypothetical magnifying glass would remain “frozen” as the time is passing. They
30 are also asked to explain or justify their answers.
31

32 The following 3 items (3A, 3B, and 3C) concern the gas state.
33

34 3.A. Pupils are asked to choose among five alternatives (See Appendix), the figure that best
35 represents what they would “see” if they observed a very small quantity of oxygen, found
36 inside a vase containing pure oxygen, a hypothetical magnifying glass enabling the view of
37 the structure of the oxygen.
38

39 3.B. Pupils are asked to explain what they think that exists between molecules, in case they
40 chose a figure depicting molecules. Otherwise, they do not have to answer this question.
41

42 3.C. Pupils are asked to answer whether or not they think that the view of the oxygen
43 structure through the hypothetical magnifying glass would remain “frozen” as the time is
44 passing. They are also asked to explain or justify their answers.
45

46 *Here, pupils are prompted to circumvent the following items 4 and 5 in case they have not*
47 *adopted a molecular structure of the substances in the previous items.*
48

49 Part 2: (The properties of a state as a result of the collective behavior of particles)
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2 The following 3 items (4A, 4B, and 4C) concern the same substance in three different
3 temperatures.
4

5 4.A. Pupils are prompted to make the assumption that they have separated one single
6 molecule from one of the following: a block of ice, some pure (liquid) water, or some pure
7 water in the gas state. They are asked whether or not they could understand if the separated
8 molecule has come from ice, liquid water or water in the gas state, respectively. Then, they
9 are also asked to explain or justify their answers.
10

11 4.B. Pupils are prompted to make the assumption that they have separated one single
12 molecule from a block of ice, another single molecule from a quantity of pure liquid water
13 and a third single molecule from a quantity of water in the gas state. They are asked whether
14 or not they could determine a physical state for each of the three molecules and if yes, what
15 this state is. Then, they are also asked to justify their answers.
16

17 4.C. Pupils are prompted to make the assumption that they have separated one single
18 molecule from a block of ice, another single molecule from a quantity of pure liquid water
19 and a third single molecule from a quantity of water in the gas state. They are asked to
20 compare the shape and the magnitude of the three molecules. Then, they are also asked to
21 justify their answers.
22

23 The following 2 items (5A and 5B) concern three different substances under normal (the
24 same) conditions.
25

26 Pupils are prompted to make the assumption that they have separated one single molecule
27 from each of the following three substances: sugar (solid), water (liquid) and oxygen (gas).
28

29 5.A. They are asked whether or not they could determine a physical state for each one of the
30 three molecules and if yes, what this state is. Then, they are also asked to justify their
31 answers.
32

33 5.B. They are asked whether they think that the three molecules are different or not. They are
34 also asked to explain or justify their answers.
35

36 Part 3: (The changes of state)
37

38 The following 3 items (6A, 6B and 5C) concern melting.
39

40 Pupils are prompted to imagine a lump of wax melting on a heating radiator.
41

42 6.A. They are asked to identify the substance after melting.
43

44 6.B. They are asked to choose among five alternatives (See Appendix), the figure that best
45 represents what they would “see” if they observed wax (a) before melting and (b) after
46 melting, using the hypothetical magnifying glass enabling the view of the structure of the
47 substances.
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6.C. They are asked to explain the way in which the wax melts by taking into account the structure of the matter and describing the procedure in detail.

The following 2 items (7A and 7B) concern boiling.

Pupils are given a figure depicting a beaker of boiling water containing many bubbles. They are asked:

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7.A. To identify the substance that exists at a point: (a) inside a bubble, (b) inside the water between the bubbles and (c) just above the surface of the boiling water.

7.B. To choose among five alternatives (See Appendix), the figure that best represents what they would “see” if they looked at each of the three points of the previous question using the hypothetical magnifying glass enabling the view of the structure of the substances.

The following 3 items (8A, 8B and 8C) concern evaporation.

8.A. Pupils are asked to explain the differences, if any, between boiling and evaporation.

8.B. Pupils are asked to choose among five alternatives (See Appendix), the figure that best represents what they would “see” if they observed evaporated water using the hypothetical magnifying glass enabling the view of the structure of the substances.

8.C. Pupils are asked to explain the way in which the water evaporates by taking into account the structure of the matter and describing the procedure in detail.

The following 2 items (9A and 9B) concern condensation.

Pupils are given the following description: The water in an open saucepan is boiling intensively. We place a cool Pyrex lid above the saucepan and we immediately notice the formation of drops on the down surface of the lid.

9.A. Pupils are asked to identify the substance in the drops.

9.B. Pupils are asked to explain the way in which the drops were formed by taking into account the structure of the matter and describing the procedure in detail.

Before data collection, a small pilot study (N=25) was carried out, followed by interviews with student discussing all items in order to detect possible communication difficulties of the test. A Cronbach’s alpha reliability coefficient of 0.86 was obtained for the above instrument and the present sample.

The marking scheme followed for correct answers was: one point for the items 1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, 3C, 6A, 8B and 9A, two points for the items 4A, 4B, 4C, 5A, 5B, 6B, 6C, 8A and 9B and three points for the items 7A, 7B and 8C. **Students, who circumvented items 4 and 5, because they did not adopt the molecular structure, were scored with zero in these items. There were only six students who did not adopt the molecular structure for all**

1
2 **states**. The sum of all items constituted students' *total achievement*, which was the main
3 dependent variable of the study, while various parts of the assessing instrument were defined
4 and treated as **independent** variables as well (see next section).
5

6
7 It is worth noticing that pupils' responses to this test were asked without any
8 notification almost one year after pupils had been taught the relevant subject matter. **Thus, the**
9 **test measures the pupils' residual knowledge and that explains the relatively low mean total**
10 **achievement score (Table 1)**. The means, standard deviations and Cronbach's internal
11 consistency reliability coefficients for the three cognitive variables as well as the *total*
12 *achievement* variable are summarized in Table 1.
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Table 1 about here

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18 **Additional research directions**

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21 Apart from students' *total achievement*, some additional dependent variables were
22 introduced. These additional dependent variables express certain aspects or dimensions of the
23 total understanding of the particulate nature of matter and its changes of state and correspond
24 to parts of the assessing instrument. These parts and their corresponding variables are the
25 following: (a) the "particulate part" (part 1). It corresponds to *particulate dimension* and
26 measures pupils' understanding of the particulate nature of matter for each of the three states:
27 solid, liquid and gas state. (b) The "collective part" (part 2). It corresponds to *collective*
28 *dimension* and measures pupils' understanding of the macroscopic properties of the states as
29 a result of the collective behavior of particles at the microscopic level. (c) The total of the first
30 two parts. It includes both, the "particulate part" and the "collective part"; it measures pupils'
31 total understanding of the structure of matter and corresponds to the dimension *structure*
32 *understanding*. (d) The third part refers to the changes of state: melting, boiling, evaporation
33 and condensation and corresponds to the dimension *understanding the changes of state*. (e)
34 The combination of the questions 6C, 8A, 8C and 9B measures only pupils' competence in
35 interpreting the changes of states and corresponds to dimension *interpretations*. A comparison
36 between boiling and evaporation (question 8A) is included here, considered as a relative
37 demanding issue that remarkably contributes to clarification of the phenomena.
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46 The effect of the three cognitive variables (FDI, CD and LTh) on the above-introduced
47 additional dependent variables is also investigated. The effects of FDI, CD and LTh on these
48 dependent variables are not expected to be analogous to their effects on the total achievement.
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The various parts of the test measure different dimensions or aspects of understanding, and thus, the cognitive variables might have a different effect on them.

Having defined the new dependent variables, the second hypothesis is reformulated in the following twofold form: *structure understanding*, which includes the *particulate dimension* and the *collective dimension*, along with the three cognitive variables (LTh, FDI, CD) have an effect (1) on students' *understanding the changes of state*, and (2) on *interpretations* as well. A sound understanding of the particulate and collective aspects of the matter can be considered a prerequisite for understanding the changes of state and furthermore for demonstrating competence in interpretation of them, which is something more complicated and demanding. Since the effects of the cognitive variables could be direct on the dependent variables or indirect through the *particulate* and the *collective dimension*, path analyses were implemented to depict such relationships.

Statistical Analysis and Results

Table 2 presents the Pearson correlation coefficients among all the variables used in this study. Noticeably, all of the cognitive variables correlate significantly with all the dependent variables ($p < 0.001$). In particular, logical thinking (LTh), field dependence/independence (FDI) and convergence/divergence (CD) correlate significantly with the main dependent variable that is total achievement (0.67, 0.42 and 0.40 respectively, $p < 0.001$) as well as with all the other dependent variables: particulate dimension, collective dimension, structure understanding, understanding of the changes of state and interpretations, as the correlation matrix shows.

Table 2 about here

Especially, *interpretations* correlate significantly with the three cognitive variables LTh, FDI and CD (0.49, 0.26 and 0.29 respectively, $p < 0.001$) as well as with the particulate dimension and the collective dimension (0.52 and 0.58 respectively, $p < 0.001$). The statistically significant correlations among the rest of the dependent variables confirm the high internal consistency among the parts of the whole assessing instrument.

The correlation analysis suggests that merely linear correlation exists between the two variables, when, however, the presence of the others is ignored. Thus, a stepwise linear regression (SLR) was employed in order to provide linear models, which relate the dependent variables with the predictors through stochastic equations (Anderson, 1984). The models

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2 propose whether a predictor has a statistically significant effect, given that the other variables
3 are present.
4

5 In order to determine which cognitive variables have an effect on the dependent
6 variables, given that the other variables are present, six stepwise multiple regression analyses
7 were performed; one stepwise multiple regression analysis for each dependent variable. The
8 results are summarized in Table 3.
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11 Table 3 about here
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13
14 The first stepwise multiple regression analysis revealed that all of the three cognitive
15 variables: logical thinking, field dependence/independence and convergence/divergence were
16 statistically significant predictors of students' total achievement scores. All of the three
17 predictors together accounted for 48.2% of the total achievement variance. Logical thinking
18 proved to be by far the best predictor accounting for 45.6% of the variance and convergence
19 /divergence and field dependence/independence follow, accounting for 1.6% and 1.0% of the
20 variance respectively. The low percentage of variance explained by FDI and CD as compared
21 to LTh is partially due to the collinearity, since FDI, CD and LTh are correlated. The latter
22 having the stronger effect takes the lion's share of the variance. Note that we deal with a
23 linear model, which captures only the linear components. However, FDI and CD show their
24 importance by the fact that both remain in the model demonstrating a small, but statistically
25 significant linear effect, given that LTh is present.
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32 The second and the sixth stepwise multiple regression analyses indicated that only
33 logical thinking was a statistically significant predictor of students' particulate dimension and
34 interpretation scores. This predictor accounted for 27.9% of the particulate dimension and
35 23.8% of the interpretations variance respectively.
36
37

38 In the third and fourth stepwise multiple regression analyses, the two out of the three
39 cognitive variables that are logical thinking and field dependence/independence, were
40 determined to be significant predictors of the collective dimension and structure
41 understanding scores. Logical thinking accounted for 27.6% of the collective dimension and
42 37.7% of the structure understanding variance. Field dependence/independence follows by
43 far, accounting for 1.3% of the collective dimension and 1.0% of the structure understanding
44 variance.
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48 As far as the fifth stepwise multiple regression analyses is concerned, it showed that
49 all of the three cognitive variables that are logical thinking, field dependence/ independence
50 and convergence/divergence were found to be significant predictors of students'
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2 understanding of the changes of state scores. All of the three predictors together accounted for
3 45.2% of the understanding of the changes of state variance. Logical thinking is again by far
4 the best predictor accounting for 41.5% of the variance and convergence/divergence and field
5 dependence/independence are the second and third accounting for 2.9% and 0.8% of the
6 variance respectively.
7

8
9 Three more stepwise multiple regression analyses were applied to determine: (a)
10 which out of five totally variables: the three cognitive (LTh, FDI, CD) as well as the
11 particulate dimension and the collective dimension, have predictive power on the
12 interpretations. (b) Which, out of **four variables**, the three cognitive (LTh, FDI, CD) as well as
13 the particulate dimension have predictive power on collective dimension. (c) Which, out of
14 four totally variables: the three cognitive (LTh, FDI, CD) as well as the *structure*
15 *understanding* have predictive power on students' *understanding the changes of state*. The
16 results are presented in Table 4.
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21
22 Table 4 about here
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24 These results show that: (a) only three out of the five variables were statistically
25 significant predictors of students' interpretations scores. The predictors were the following:
26 collective dimension, particulate dimension and logical thinking. All of the three predictors
27 together accounted for 41.9% of the interpretations variance. Collective dimension was
28 proved to be by far the best predictor accounting for 32.7% of the variance and particulate
29 dimension and logical thinking follow, accounting for 7.6% and 1.6% of the variance
30 respectively. (b) Only logical thinking and particulate dimension were statistically significant
31 predictors of students' collective dimension scores. Logical thinking was the best predictor
32 accounting for 26.5% of the variance and the particulate dimension follows, accounting for
33 5.7% of the variance. (c) *Structure understanding*, logical thinking and convergent/divergent
34 cognitive style were statistically significant predictors of students' *understanding the changes*
35 *of state*. The three predictors accounted for 53.8% and 5.8% and 1.7% of the variance
36 respectively.
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43 Following, path analyses were employed, where the standardized regression betas of
44 the corresponding regression equations were used as path coefficients (Bryman & Cramer,
45 1990).
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48 Path I diagram (Figure 1) shows that logical thinking had a significant direct effect
49 (0.25) on *Understanding the changes of state* and an indirect effect via *Structure*
50 *understanding* ($0.56 \times 0.53 = 0.30$). LTh has a total effect of 0.55 ($0.25 + 0.30$). FDI has an
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2 indirect effect via *Structure understanding* ($0.13 \times 0.53 = 0.07$) and CD has a direct effect of
3 0.15. The total causal effect was 0.77 calculated as the sum of the direct and indirect effects.
4

5 Path II diagram (Figure 2) shows that logical thinking had a significant direct effect
6 (0.17) and also three indirect effects on *interpretations*: (1) via *particulate dimension* ($0.53 \times$
7 $0.26 = 0.14$), (2) via *collective dimension* ($0.36 \times 0.36 = 0.13$) and (3) via both *particulate*
8 and *collective dimension* ($0.53 \times 0.29 \times 0.36 = 0.06$). A total causal effect of 0.50 was
9 calculated.
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13 Figure 1 and 2 about here
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15 Interpretation of results and Discussion

16
17 In this section an attempt is made for a theoretical interpretation of the results that
18 came out from the statistical analysis. That is, to relate some aspects of the cognitive skills
19 that are behind the psychometric measurements to the nature of mental tasks involved when
20 learning this specific domain material.
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23
24 Results from SLR on total achievement (Table 3) supported the main hypothesis of
25 this study, that all of the three cognitive variables (LTh, FDI and CD) affect students'
26 performance. Out of the three cognitive predictors, logical thinking ability (LTh) was by far
27 the best, accounting for the lion's share of the total achievement score variance and it appears
28 to have an effect on every other dependent variable. Noticeably, it was the only significant
29 predictor of 'particulate dimension' and 'interpretations' (Table 3). These results are
30 consistent with other findings in previous studies that reported the supremacy of logical
31 thinking as a predictor variable on science achievement (Chandran et al. 1987; Lawson &
32 Thomson 1988; Johnson & Lawson 1998; Kang et al., 2005;). Lawson (1985) concluded that
33 "deficiencies in formal reasoning are a probable cause of achievement deficiencies in the
34 sciences, mathematics etc". Correspondingly, the results of this study support the hypothesis
35 that an adequate level of logical thinking appears to be necessary for students to understand
36 the particulate nature of matter and its changes of state.
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39
40 CD cognitive style was also a significant predictor of the students' total achievement
41 scores (Table 3). It appears that divergent pupils were favored in understanding the particulate
42 nature of matter and its physical changes. This might seem contradicting at first sight, with
43 research reports stating that those who mostly show aptitude for science are convergers
44 (Hudson 1966). However, a closer look on the learning material explains this inconsistency.
45
46 The mental tasks involved in learning this domain of early science that includes the
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2 particulate nature and the changes of state of matter, are not analogous to those of demanding
3 problems that need unique solutions clearly obtainable from the information available, which
4 would favor convergent thinkers (Child & Smithers, 1973).

5
6 On the other hand, the content of scientific material that the assessing instrument
7 covered in this study involves a diversity of concepts, properties and models, which mostly
8 require detailed descriptions in order to be understood when studied or taught. Therefore, it is
9 reasonable to assume that linguistic skills may have played a major role in students'
10 understanding of the relevant scientific topics. Linguistic skills, such as comprehension and
11 interpreting of a scientific text, are considered to be of paramount importance for reasoning in
12 science (Byrne et al. 1994). Students, though, who show superiority in language, are thought
13 to be divergent thinkers (Hudson, 1966; Runco, 1986; Danili & Reid, 2006). Links between
14 divergency and science has also been reported in the literature. As it was mentioned in a
15 previous section of this study, Hudson (1966) noted that the convergers tended to choose the
16 sciences, but the divergers who did choose the sciences performed very well. Following, other
17 research findings were consistent with Hudson's claim (Al-Naeme, 1991; Field & Poole,
18 1970).

19
20 Based on the degree of linguistic skills required in a mental task, one could explain
21 why CD cognitive style had an effect on some variables, such as 'total achievement' and
22 'understanding the changes of state', while it had no effect on some others. CD had no effect
23 on 'Particulate dimension', 'collective dimension', and 'structure understanding' because
24 teaching and studying of the corresponding themes can be assisted by simple illustrations and
25 no extended additional descriptions are required, so that the role of language here does not
26 seem to be determinative. While the effect of CD is favored when the content requires
27 linguistic ability, a limit should exist determined by the complexity of the task. When the task
28 becomes more complex and requires logical operations leading to a conclusion or a unique
29 final answer, then other abilities, such as formal reasoning and even convergent thinking,
30 might prevail and the effect of divergency becomes less significant. Such appear to be the
31 'interpretations' variable case.

32
33 Field dependent/independent (FDI) cognitive style was the third significant predictor
34 of students' total achievement scores (Table 3). Field independent students were those who
35 performed better. This result is consistent with other findings in previous studies, which
36 showed that field independence is an intellectual asset concerning general achievement in
37 science (Lawson, 1983; Johnstone & Al-Naeme, 1995; Niaz, 1996; Tinajero & Paramo, 1998;
38 Bahar & Hansell, 2000; Danili & Reid, 2004; Kang et al., 2005; Tsaparlis, 2005; Author 2 et

1
2 al., 2005; Danili & Reid, 2006). It can be inferred that field independent pupils' ability to
3 separate readily the significant information from its context (Witkin & Goodenough, 1981) or
4 the *signal* from the *noise* offered them a serious advantage, either in their study or during
5 teaching.
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7

8 Field dependence/independence (FDI) had also an effect on the most of the dependent
9 variables that measured certain aspects or dimensions of the total understanding of the
10 particulate nature of matter and its changes of state. These are the following: 'collective
11 dimension', 'structure understanding' and 'understanding of the changes of state'. All the
12 above involve a complex context, that might be misleading for students' thought, and thus the
13 field independent style has an advantage. On the contrary, FDI had no effect on 'particulate
14 dimension' and 'interpretations'. The former referred to three specific models, one for each
15 physical state, that are well described by the corresponding figures, so that no room for
16 misleading information is left and thus, no effect of FDI is observed. Nevertheless, when the
17 same models are asked to be recognized by the students, within a more complex and possibly
18 misleading context, e.g. in 'understanding of the changes of state', FDI appears again to be a
19 predictor (Table 3, model 5).
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26 For the 'interpretations' case, however, the explanation is different and analogous to
27 the one for CD. Interpretation of phenomena requires a deeper understanding and reasoning
28 skills, so that logical thinking (LTh) prevails among all possible predictors, as the SLR
29 confirms it (Table 3, model 6).
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32 The dimensions 'collective' and 'particulate' are affected by cognitive variables and in
33 addition, when treated as independent variables combined with the cognitive variables are
34 shown to have an effect on students' performance in understanding the changes of state and
35 interpretations of these physical phenomena. These effects, direct and indirect, which are
36 shown in the path analyses (Figures 1 & 2), provide support for the second hypothesis of this
37 study. They indicate that 'collective' and 'particulate' dimensions of students' understanding
38 of this subject matter constitute fundamental and substantial presuppositions for interpreting
39 the phenomena of the changes of state. Similar findings have been also reported in relevant
40 qualitative (Johnson, 1998c) and quantitative studies (Author 3, Author 2 et al., 2008). As it
41 was mentioned in the introduction section, Johnson (1998c) concluded that understanding of
42 the nature of the gas state was "the underlying issue" for the understanding of the state
43 changes "with the particle theory playing a key role". Interestingly, 'interpretations' variable
44 was also affected directly by LTh, which underlines the importance of formal reasoning in the
45 related cognitive processes. On top, when a deeper knowledge on changes of physical states is
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2 pursued, being familiar merely with the particulate models of two physical states, pre and post
3 the change, is not adequate. There is also a dire need for understanding the transition from one
4 model to the other, where reasoning abilities are thought to be of great importance. This is
5 consistent with the direct effect of logical thinking on interpretations. In the main, logical
6 thinking appears to be the bottom line for competence in 'interpretations', since the former, as
7 the path analysis shows, has a direct effect on the latter and indirect effects as well, via
8 particulate and collective dimensions. The effect of 'particulate dimension' on 'collective
9 dimension', shown in the path analysis II, could be explained by the fact that understanding
10 particulate models are thought to precede understanding collective properties and the former
11 to be a presupposition for the latter.

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17 Concluding, it is important to state that the hypotheses are well supported by the data.
18 It is very important, that up to 48,2% of the students' achievement variance was explained and
19 all the related model-parameters were statistically significant. Thus, we maintain that the
20 findings of the present research are of paramount importance, because they shed light on the
21 factors hindering students' understanding of the particulate nature of matter and the changes
22 of states. On the other hand, the present study opens a new area of investigations for the
23 conceptual change in this particular domain, where the individual differences, such as logical
24 thinking and cognitive styles, have been ignored from research hypotheses.

30 **Implications for teaching**

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33 There are four implications of the present findings for the practice of science
34 education. The first concerns students' insufficiency in formal reasoning, which was found to
35 be the main origin of their difficulties. In order to assist students lacking formal operational
36 abilities, teachers are required to utilize such teaching methods that make abstract concepts
37 more accessible through concrete-operational thought. These methods make use of
38 illustrations, diagrams and models that constitute perceptible entities or concrete materials to
39 focus attention on critical and variable attributes of abstract concepts. There is evidence that
40 these methods can enhance the attainment of abstract concepts (Cantu & Herron, 1978; Howe
41 & Durr, 1982; Zeitoun, 1984). Another alternative for dealing with the problem is to design
42 training programmes that promote development in students' formal operational reasoning
43 (Lawson, 1985).

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49 The second implication concerns students' field dependent/independent ability.
50 Although the field-independent ability may be developed naturally with experience, it is

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2 difficult to teach someone to be field independent. However, effort should be made during
3 teaching in order to help students making sense of the material taught, when attending lessons
4 in classroom or reading their school textbooks, by focusing on central ideas and disembedding
5 only the relevant information.
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8 The third implication is related to convergent/divergent thinking. According to the
9 findings of this investigation, in this early science domain, lack of diverging thinking seemed
10 to be a disadvantage due to the restricted linguistic skills. Since short-term progress in these
11 linguistic skills is not likely to be achieved, the assistance to students could be given by
12 methods that present and develop the teaching material by circumventing the dominating role
13 of language as much as possible. That is, by methods which implement illustrations and
14 diagrams that clarify the particulate structures of substances in the three physical states, and
15 software simulations that demonstrate the transition from one state model to another.
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20 Finally, the fourth implication concerns the background role of the particulate and the
21 collective dimensions of students' understanding of the nature of matter. Teaching should
22 primarily and intensively focus attention on these two dimensions considering them as the
23 underlying issue for the understanding the changes of state.
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References

- Author 3 et al. (2005). *International Journal of Science Education*.
- Author 3. (2007). *Conference Proceedings for Science Education*.
- Author 3, Author 2, et al. (2008). *International Journal of Science Education*, (Paper submitted for publication).
- Author 2. (2006). *Nonlinear Dynamics, Psychology and Life Science*.
- Author 2, et al. (2005). *International Journal of Science and Mathematics Education*.
- Anderson, T. W. (1984). *An Introduction to multivariate analysis*, 2nd ed., New York: Wiley.
- Al-Naeme, F. F. A. (1991). *The influence of various learning styles on practical problem-solving in chemistry in Scottish secondary schools*. Ph.D. Thesis, University of Glasgow.
- Bahar, M. (1999). *Investigation of Biology student's cognitive structure through word association tests, mind maps and structural communication grids*, Ph.D. Thesis, University of Glasgow.
- Bahar, M., & Hansell, M. (2000). The relationship between some psychological factors and their effects on the performance of grid questions and word association tests. *Educational Psychology: An International Journal of Experimental Educational Psychology*, 20, 349-363.
- Bar, V., & Travis, A. (1991). Children's views concerning phase changes. *Journal of Research in Science Teaching*, 28, 363-382.
- Bar, V., & Galili, I. (1994). Stages of children's views about evaporation. *International Journal of Science Education*, 16, 157-174.
- Bennett, S. N., (1973). Divergent thinking abilities—a validation study. *The British Journal of Educational Psychology*, 43, 1-7.
- Benson, D., Wittrock, M., & Baur, M. (1993). Students' preconceptions of the nature of gases. *Journal of Research in Science Teaching*, 30, 587-597.
- Bonder, G. M. (1991). I have found you an argument. *Journal of Chemical Education* 68, 385-388.
- BouJaoude, S., Salloum, S., & Abd-El-Khalick, F. (2004). Relationships between selective cognitive variables and students' ability to solve chemistry problems. *International Journal of Science Education*, 26(1), 63-84.
- Bryman, A. & D. Cramer (1990). *Quantitative data analysis for social scientists*. London: Routledge.
- Byrne, M., Johnstone, A., & Pope, A., (1994), Reasoning in science: a language problem revealed? *School Science Review*, 75(272), 103-107.

- 1
2 Cantu, L. L., & Herron, J. D., (1978). Concrete and formal Piagetian stages and science
3 concept attainment. *Journal of Research in Science Teaching*, 15, 413-419.
4
5 Chandran, S., Treagust, D.,F., & Tobin, K. (1987). The role of cognitive factors in chemistry
6 achievement. *Journal of Research in Science Teaching*, 24(2), 145-160.
7
8 Chiappetta, E., L. & Russell, J., M. (1982). The relationship among logical thinking, problem
9 solving instruction, and knowledge and application of earth science subject matter.
10 *Science Education*, 66(1), 85-93.
11
12 Child, D., & Smithers, A., (1973). An attempted validation of the Joyce-Hudson scale of
13 convergence and divergence. *British Journal of Educational Psychology*, 43, 57-61.
14
15 Costu, B., Ayas, A., Niaz, M., Unal, S., & Calik, M. (2007). Facilitating Conceptual Change
16 in Students' Understanding of Boiling Concept. *Journal of Science Education and
17 Technology*, 16, 524-536.
18
19 Danili, E., & Reid N. (2004), Some strategies to improve performance in school chemistry,
20 based on two cognitive factors. *Research in Science & Technological Education*, 22,
21 201-223.
22
23 Danili, E., & Reid, N. (2006). Cognitive factors that can potentially affect pupils' test
24 performance. *Chemistry Education Research and Practice*, 7 (2), 64-83
25
26 Dow, W. M., Auld, J., & Wilson, D. (1978). *Pupils' Concepts of Gases, Liquids and Solids*
27 (Dundee: Northern College of Education, Dundee Campus).
28
29 Facaoaru, C. (1985). *Kreativität in Wissenschaft und Technik*. Bern: Huber.
30
31 Field, T. W., & Poole, M. E. (1970). Intellectual style and achievement of arts and science
32 undergraduates. *British Journal of Educational Psychology*, 40, 338-341.
33
34 Fryer, M. (1996). *Creative teaching and learning*, London, Paul Chapman.
35
36 Getzels, J. W., & Jackson, P. W. (1962). *Creativity and intelligence*. London and N.York:
37 John Wiley and sons INC.
38
39 Goodenough, D. R., & Karp, S. A. (1961). Field dependence and intellectual functioning.
40 *Journal of Abnormal and Social Psychology*. 63, 241-246.
41
42 Griffiths, A. K., & Preston, K. R. (1989, March). An investigation of grade 12 students'
43 misconceptions relating to fundamental characteristics of molecules and atoms. Paper
44 presented at the 62nd conference of the National Association for Research in Science
45 Teaching, San Francisco, California.
46
47 Guastello, S. J., Bzdawaka, A., Guastello, D. D., & Rieke, M. L. (1992). Cognitive abilities
48 and creative behaviours: CAB-5 and consequences. *Journal of Creative Behaviour*, 26,
49 260-267.
50
51
52
53
54
55
56
57
58
59
60

- 1
2 Hatzinikita, V., & Koulaidis, V. (1997). Pupils' ideas on conservation during changes in the
3 state of water. *Research in Science and Technology Education*, 15(1), 53–70.
4
5 Heller, K. A. (2007). Scientific ability and creativity. *High Ability Studies*, 18, 2, 209-234.
6
7 Howe, A., & Durr, B. (1982). Using concrete materials and peer interaction to enhance
8 learning in chemistry. *Journal of Research in Science Teaching*, 19, 225-232.
9
10 Hudson, L., (1966). *Contrary Imaginations: a psychological study of the English schoolboy*,
11 Great Britain, Penguin books Ltd.
12
13 Hudson, L., (1968). *Frames of mind*, London, Methuen.
14
15 Johnson, M.A., & Lawson, A.E. (1998). What are the relative effects of reasoning ability and
16 prior knowledge on biology achievement in expository and inquiry classes? *Journal of*
17 *Research in Science Teaching*, 35(1), 89–103.
18
19 Johnson, P. M. (1998a). Progression in children's understanding of a 'basic' particle theory:
20 A longitudinal study. *International Journal of Science Education*, 20, 393–412.
21
22 Johnson, P. M. (1998b). Children's understanding of changes of state involving the gas state,
23 Part 1. Boiling water and the particle theory. *International Journal of Science Education*,
24 20, 567–583.
25
26 Johnson, P. M. (1998c). Children's understanding of state involving the gas state, Part 2.
27 Evaporation and condensation below boiling point. *International Journal of Science*
28 *Education*, 20, 695–709.
29
30 Johnstone, A. H., & Al-Naeme, F. F. (1991). Room for scientific thought? *International*
31 *Journal of Science Education*, 13 (2), 187-192
32
33 Johnstone, A.,H. & Al-Naeme, F.,F. (1995). Filling a curriculum gap in chemistry.
34 *International Journal of Science Education*, 17 (2), 219-232.
35
36 Kang, S., Scharmann, L.C., Noh, T. & Koh, H. (2005). The influence of students' cognitive
37 and motivational variables in respect of cognitive conflict and conceptual change.
38 *International Journal of Science Education*, 27(9), 1037-1058.
39
40 Lawson, A. E., & Renner, J. W. (1975). Relationship of science subject matter and
41 developmental levels of learners. *Journal of Research in Science Teaching*, 12(4), 347-
42 358.
43
44
45 Lawson, A.E. (1978). Development and validation of the classroom test of formal reasoning.
46 *Journal of Research in Science Teaching*, 15, 11-24.
47
48 Lawson, A.,E. (1982). Formal reasoning, achievement, and intelligence: an issue of
49 importance. *Science Education*, 66(1), 77-83.
50
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54
55
56
57
58
59
60
- Lawson, A., E. (1983). Predicting science achievement: The role of developmental level, disembedding ability, mental capacity, prior knowledge, and beliefs. *Journal of Research in Science Teaching*, 20(2), 117–129.
- Lawson, A.E. (1985). A review of research on formal reasoning and science instruction. *Journal of Research in Science Teaching*, 22, 569-617.
- Lawson, A., E. & Thompson, L., D. (1988). Formal reasoning ability and misconceptions concerning genetics and natural selection. *Journal of Research in Science Teaching*, 25(9), 733-746.
- Lawson, A.E. (1993). *Classroom test of scientific reasoning: Revised paper-pencil edition*. Tempe, AZ: Arizona state University.
- Lee, O., Eichinger, D., Anderson, C., Berkheimer, C., & Blakeslee, T. (1993). Changing middle school students' conceptions of matter and molecules. *Journal of Research in Science Teaching*, 30, 249–270.
- Niaz, M. (1996). Reasoning strategies of students in solving chemistry problems as a function of developmental level, functional M-capacity and disembedding ability. *International Journal of Science Education*, 18(5), 525-541.
- Novick, S., & Nussbaum, J. (1978). Junior high school pupils' understanding of the particulate nature of matter: an interview study. *Science Education*, 62, 273-281.
- Novick, S., & Nussbaum, J. (1981). Pupils' understanding of the particulate nature of matter: a cross-age study. *Science Education*, 65, 187-196.
- Nuttall, D. L., (1972). Convergent and divergent thinking. *The British Journal of Educational Psychology*, 43, 1-7.
- Orton A., (1992). *Learning mathematics issues, theory and classroom practice*, London, Cassell Education Series.
- Osborne, R. J., & Cosgrove, M. M. (1983). Children's conceptions of the changes of state of water. *Journal of Research in Science Teaching*, 20, 825–838.
- Pereira, M. & Pestana, M.E. (1991) Pupils' representations of models of water. *International Journal of Science Education*, 13, 313-319.
- Renstrom, L., Andersson, B., & Marton, F. (1990). Students' conceptions of matter. *Journal of Educational Psychology*, 82, 555-569
- Runco, M. A., (1986). Divergent thinking and creative performance in gifted and non gifted children. *Educational and Psychological Measurement*, 46, 375-383.
- Sayre, S. & Ball, D., W. (1975). Piagetian cognitive development and achievement in science. *Journal of Research in Science Teaching*, 12 (2), 165-174.

- 1
2 Simon, A. H. (1974). How big is a chunk? *Science*, 183, 482–488.
- 3 Stavy, R. (1988). Childrens' conceptions of gas. *International Journal of Science Education*,
4 10(5), 533-560.
- 5
6 Stavy, R. (1990a). Children's conception of changes in the state of matter from liquid (or
7 solid) to gas. *Journal of Research in Science Teaching*, 27, 247–266.
- 8
9 Stavy, R. (1990b). Pupils' problems in understanding conservation of matter, *International*
10 *Journal of Science Education*, 12, 501-512.
- 11
12 Tinajero, C., & Paramo, F.M. (1998). Field dependence-independence cognitive style and
13 academic achievement: a review of research and theory. *European Journal of*
14 *Psychology of Education*, 13, 227-251.
- 15
16 Tsai, C.C. (1999). Overcoming junior high school students' misconceptions about
17 microscopic views of phase change: A study of an analogy activity. *Journal of Science*
18 *Education and Technology*, 8(1), 83–91.
- 19
20 Tsaparlis, G., & Angelopoulos, V. (2000). A model of problem solving: Its operation, validity
21 and usefulness in the case of organic-synthesis problems. *Science Education*, 84, 131-
22 153.
- 23
24
25 Tsaparlis, G. (2005). Non-algorithmic quantitative problem solving in university physical
26 chemistry: a correlation study of the role of selective cognitive factors. *Research in*
27 *Science and Technological Education*. 23, 125-148.
- 28
29
30 Witkin, H. A., Dyk, R. B., Faterson, H. F., Goodenough, D. R., & Karp, S. A. (1962).
31 *Psychological differentiation*. New York: Wiley.
- 32
33 Witkin, H.,A., Oltman, P.,K., Raskin, E. & Karp, S.,A. (1971). *Embedded figures test*,
34 *children's embedded figures test, group embedded figures test: Manual*, Palo Alto, CA,
35 Consulting Psychologists Press.
- 36
37
38 Witkin, H.A., Moore, C.A., Goodenough, D.R., & Cox, P.W. (1977). Field-dependent and
39 fieldindependent cognitive styles and their educational implications. *Review of*
40 *Educational Research*, 47(1), 1–64.
- 41
42
43 Witkin, H. A., & Goodenough, D. R. (1981). *Cognitive styles: essence and origins*, New
44 York, International University Press.
- 45
46 Zeitoun, H.,H. (1984). Teaching scientific analogies: a proposed model. *Research in Science*
47 *and Technological Education*, 2, 107-125.
- 48
49
50 Zeitoun, H.,H. (1989). The relationship between abstract concept achievement and prior
51 knowledge,
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3 227-234.
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10 Appendix- Figure 3 about here
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Table 1. Descriptive statistics for the tests

Variable	Maximum score possible	N	Mean	Standard Deviation	Cronbach's alpha
FDI	20	309	6.21	4.15	0.84
CD	100	298	43.10	11.31	0.76
LTh	60	310	19.47	10.64	0.79
Total Achievement	39	300	7.77	6.55	0.86

Table 2. Correlation matrix

Variable Number and Name	1	2	3	4	5	6	7	8	9
<u>Dependent Variables</u>									
1. Total Achievement	1,00								
2. Particulate dimension	0,80*	1,00							
3. Collective dimension	0,80*	0,48*	1,00						
4. Structure Understanding	0,93*	0,85*	0,87*	1,00					
5. Understanding the Changes of State	0,93*	0,64*	0,61*	0,73*	1,00				
6. Interpretations	0,75*	0,52*	0,58*	0,64*	0,76*	1,00			
<u>Predictors</u>									
7. LTh	0,67*	0,53*	0,52*	0,61*	0,64*	0,49*	1,00		
8. FDI	0,42*	0,29*	0,35*	0,37*	0,40*	0,26*	0,46*	1,00	
9. CD	0,40*	0,24*	0,31*	0,32*	0,42*	0,29*	0,42*	0,35*	1,00

* $p < 0.001$

Table 3. Adjusted R^2 , Percentage of Variance explained, Regression Slopes, Standard Errors, Beta standardized coefficients, t -tests and Model Fit for various models.

Model	Adj R^2	% of Variance Explained	b	seb	Beta	t	F
1. Total achievement (Dependent Variable)	0.482	48.2					79.6***
Predictors							
<i>LTh</i>		45.6	0.343	0.032	0.568	10.60***	
<i>CD</i>		1.6	0.075	0.030	0.127	2.52*	
<i>FDI</i>		1.0	0.190	0.081	0.122	2.35*	
2. Particulate dimension (Dependent Variable)	0.279	27.9					
Predictor							
<i>LTh</i>		27.9	0.097	0.009	0.531	10.61***	112.6***
3. Collective dimension (Dependent Variable)	0.289	28.9					56.4***
Predictors							
<i>LTh</i>		27.6	0.094	0.012	0.462	7.96***	
<i>FDI</i>		1.3	0.073	0.030	0.139	2.40*	
4. Structure Understanding (Dependent Variable)	0.387	38.7					87.1***
Predictors							
<i>LTh</i>		37.7	0.183	0.018	0.556	10.32***	
<i>FDI</i>		1.0	0.107	0.046	0.126	2.34*	
5. Understanding the changes of state (Dependent Variable)	0.452	45.2					70.9***
Predictors							
<i>LTh</i>		41.5	0.169	0.018	0.521	9.46***	
<i>CD</i>		2.9	0.055	0.016	0.175	3.37**	
<i>FDI</i>		0.8	0.096	0.045	0.114	2.14*	
6. Interpretations (Dependent Variable)	0.238	23.8					91.2***
Predictor							
<i>LTh</i>		23.8	0.051	0.005	0.491	9.55***	

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4. Regression slopes, standard errors, *t*-tests, beta standardized coefficients, adjusted R^2 , percentage of variance explained and model fit for predicting of performance on *Interpretations, Collective Dimension and Understanding the changes of state.*

Model	Adj R^2	% of Variance Explained	b	seb	Standardized Beta	t	F
1. Interpretations (Dependent Variable)	0.419	41.9					70.1***
Predictors <i>Collective dimension</i>		32.7	0.189	0.028	0.364	6.64***	
Predictors <i>Particulate dimension</i>		7.6	0.148	0.032	0.258	4.67***	
Predictors <i>LTh</i>		1.6	0.017	0.006	0.166	2.93**	
Excluded: <i>FDI, CD</i>							
2. Collective Dimension (Dependent Variable)	0.322	32.2					69.5***
Predictors <i>LTh</i>		26.5	0.073	0.012	0.364	6.37***	
Predictors <i>Particulate dimension</i>		5.7	0.318	0.063	0.288	5.03***	
Excluded: <i>FDI, CD</i>							
3. Understanding the Changes of State (Dependent Variable)	0.613	61.3					143.2***
Predictors <i>Structure understanding</i>		53.8	0.529	0.048	0.532	11.13***	
Predictors <i>LTh</i>		5.8	0.082	0.016	0.254	5.09***	
Predictors <i>CD</i>		1.7	0.048	0.013	0.150	3.57***	
Excluded: <i>FDI</i>							

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

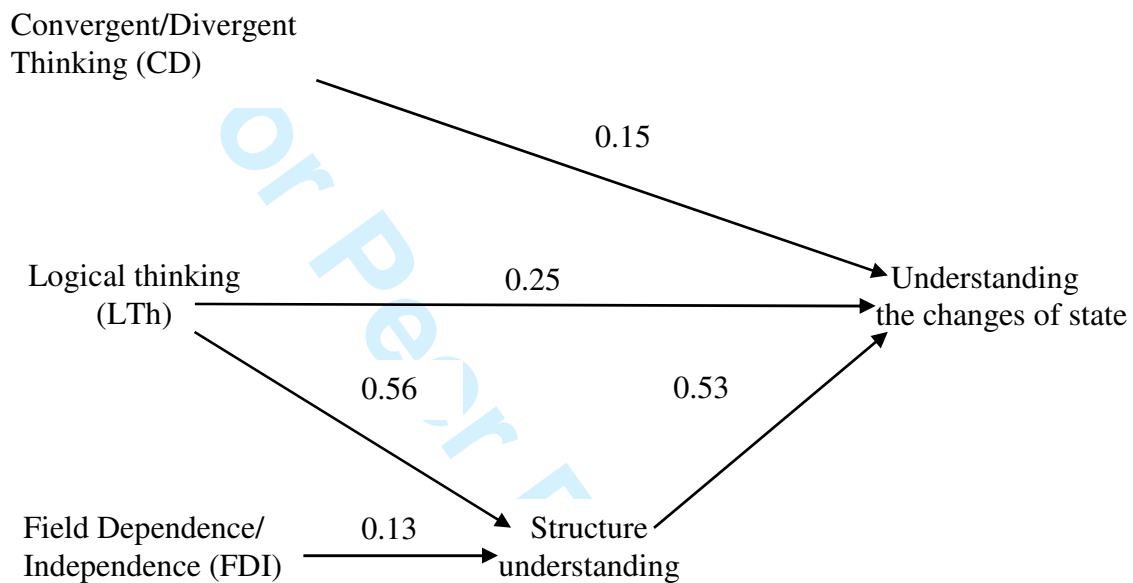


Figure 1. A path analysis for hypothesized relationships between the three cognitive variables: Logical thinking (LTh), Convergent/Divergent Thinking (CD), Field Dependence/Independence (FDI), 'Structure understanding' and students' understanding the changes of state. The total causal effect is 0.77.

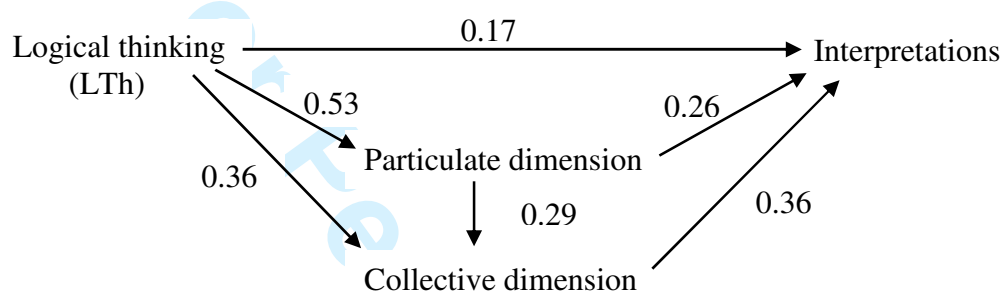


Figure 2. A path analysis for hypothesized relationships between students' competence in interpretation of the changes of state, logical thinking (LTh) and particulate and collective dimensions of students' understanding of the nature of matter. The total effect is 0.50.

APPENDIX

Figure 3. Figures included in the test as stimuli.

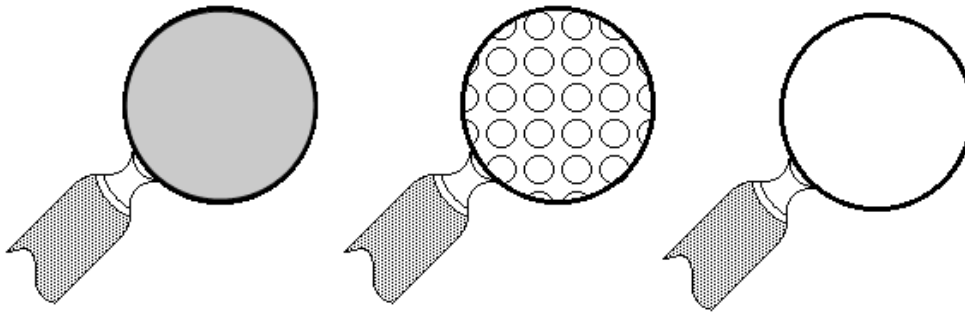


Figure 1:
Continuous substance

Figure 2:
Molecules (be it of nearly spherical shape)
which are in array, not touching each other

Figure 3:
Nothing

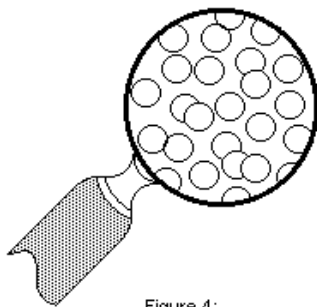


Figure 4:
Molecules (be it of nearly spherical shape)
which are in random positions relatively close
to each other, not touching each other.

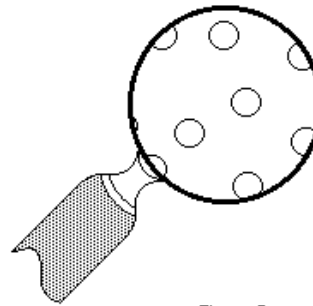


Figure 5:
Molecules (be it of nearly spherical shape)
which are in random positions, mostly far
away from each other.

Only