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RESEARCH REPORT
Concepts

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PRIMARY STUDENT TEACHERS' UNDERSTANDING OF THE PROCESS AND EFFECTS OF DISTILLATION

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ABSTRACT: One-to-one interviews were administered to a sample of thirty female, primary student teachers of different backgrounds in science. A distillation apparatus accompanied by a diagram was presented to each student and its use for distilling liquids was fully discussed. Students were then asked to describe the macroscopic and microscopic changes which would occur when different water solutions were to be distilled. The majority of the students exhibited limited understanding of the particulate nature of matter and the connection between the observable macroscopic changes (i.e., evaporation or liquefaction) and the way molecules move in relation to one another, and how they are held together. They did not also develop appropriate concepts related to boiling point, latent heat of evaporation, and fractional distillation. They had difficulties in realizing the effects of distillation on water solutions and proposed that the product of distillation would not change taste and color, or that its taste and color would be lighter. These difficulties were progressively greater for salt solution, sugar solution, tap water, aqueous alcoholic solution, tea, and coke or wine. Implications of students' conceptions on curriculum planning and teaching practices conducive to conceptual growth are discussed. [*Chem. Educ. Res. Pract. Eur.*: 2000, *1*, 355-364]

KEY WORDS: *distillation; alternative frameworks; student conceptions; evaporation; liquefaction*

INTRODUCTION

The conception of matter consisting of tiny particles, atoms and molecules, in never ending motion and interaction, provides a basis for understanding the invisible microscopic events underlying natural phenomena. Several studies (Griffiths & Preston, 1992; Hesse & Anderson, 1992; Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993) provided useful information concerning students' conceptions at the macroscopic and molecular level. Students were, for example, found to have great difficulties in changing their thinking when they were asked to move away from observable changes in substances to the atomic-molecular level and "failed to invoke atoms and molecules as explanatory constructs, even though this had been emphasized in their chemistry course" (Hesse & Anderson, 1992, p. 277).

Other studies examined specifically children's conceptions about evaporation (Bar & Galili, 1994; Bar & Travis, 1991). These studies provided evidence that the development of students' conceptions about evaporation and the matter in bubbles, in the age range 6-12, follows certain attainment stages, proceeding from concrete to abstract ideas. Changes in students' views were attributed to their ability to perceive the existence of air, and the understanding of boiling preceded the understanding of evaporation.

Stavy (1990) investigated children's (ages 9-15) ability to conserve matter, its identity, and its weight in tasks using evaporation of acetone (propanone) and sublimation of iodine, and their understanding of the reversibility of the process. She reported that science teaching did not help the students to internalize the particulate theory of matter. Children younger than ten years of age had also a narrow conception of matter, which was grasped as a concrete, solid object, excluding liquids and gases from being matter. This conception was progressively broadened with age and education to include first liquids and then gases also as matter. Children also believed that matter is made up of a material core and non-material properties, such as color, smell, flammability, and heaviness (weight) which can, however, be disassociated from the material especially when the material undergoes a change. Evidence showed that children believe that matter does not have to be solid, liquid, or gas to be conceived as matter, but there must be perceptual evidence of its existence. Matter is not conceived as permanent and it ceases to exist when the evidence disappears. The colored iodine gas was, thus, conceived as matter whereas the colorless gas of acetone was not perceived as existing due to the lack of perceptual evidence of its existence. Students were, furthermore, found to construct intuitive rules regarding the relation between the weight of matter (heaviness) and its state. Based on these rules weightless matter (gases) can exist, and weight changes with the state of matter (gas weighs less than liquid or solid).

Research studies dealing with students' conceptions in science provide "an exceptionally subtle way of developing teacher's science-conceptions" (Goodwin, 1995, p. 108). Summers (1992) reported that the majority of primary student teachers (PST) "hold views of science concepts that are not in accord with those accepted by scientists" (p. 26). Goodwin (1995) explored science graduates' conceptions, focusing primarily on the development of ideas of the particulate nature of matter. The subjects were halfway through a one-year Postgraduate Certificate in Education and all had completed a six-week teaching practice in a secondary school. The study provided evidence that even for science graduates the development of a coherent and consistent explanation of phenomena, such as freezing, boiling and evaporation, involving the behavior of particles according to the kinetic theory, is problematic. Thus, alternative conceptions may arise as a result of interaction with teachers (Gilbert & Zylberstajn, 1985) who, in some cases, exhibit the same range of conceptions as their students.

The present study focuses upon PST's conceptions relating to the process and effects of distillation on water solutions. Distillation is related to several physical changes, such as evaporation, boiling, vapor condensation, and the water cycle in nature. The extent of understanding the process of distillation and some closely related concepts, such as boiling point or latent heat of evaporation, will provide useful information concerning the comprehension of the particulate nature of matter and its transformations.

Distillation cuts across chemistry, physics, and biology and a recent study (Keulen, Mulder, Goedhart, & Verdonk, 1995) investigated the problems chemistry majors have in traditional laboratory work. Distillation is usually introduced to primary school students, while in the early secondary school, teachers demonstrate distillation and in some cases students carry out distillation themselves. Distillation and fractional distillation are common separation techniques, which may be reintroduced to secondary school students several times. These techniques are demonstrated using thermometers and the usual glassware. New more sophisticated approaches of experimental set up, which are based on data logging techniques (Soares & Greevy, 1995), appeared recently, and they have apparent advantages over the traditional approach. The extent of PST's understanding of the process and effects of distillation and their conceptions will provide grounds for judging the appropriateness and effectiveness of science instruction at both the primary and secondary level in Cyprus. The collected information could be also used to guide the design and implementation of instructional interventions conducive to conceptual change among PST.

PROCEDURE

One-to-one interviews were administered to a random sample of thirty female PST of different backgrounds in science. The subjects were students at the Department of Educational Studies of the University of Cyprus, who enrolled in an obligatory science course for PST. Seven subjects attended the science section of the upper secondary school, where science and mathematics constitute the main subjects of study. The rest of the subjects attended other sections of study where the emphasis on science teaching is limited. The subjects did not have any science courses at the university level.

Students were informed that the information from the interviews was to be used for the design of the course. They volunteered to be interviewed in an attempt to acquaint them with the interview technique. Interviews were held individually and took place in a sequence determined by the availability of each subject. Each interview session, which lasted about 30 minutes, was tape-recorded and transcribed for further analysis. The process of collecting information adhered to the traditional approach, which is mainly followed in teaching science in Cyprus. The different parts of a quick-fixed distillation apparatus were on a table in front of each student. She was then presented with a diagram of the apparatus and was asked both to assemble the apparatus and to explain its use for distilling liquids. Most of the subjects failed to supply adequate answers and their difficulties were discussed, so that they fully understood how the distillation apparatus could be used. Subsequently, only the diagram of the apparatus was used for the interview.

The interview consisted of two major categories of questions. In the first category, students were asked to describe the macroscopic changes and the energy changes, which would occur during the distillation of different water solutions, and to predict the color, the taste, and the density of the distillate. The second category of questions asked the subjects to relate the macroscopic changes to the particulate nature of matter (molecules and their properties and behavior). Students had, in both groups of questions, to predict and describe the changes for every separate stage of distillation (i.e., evaporation, liquefaction). A different liquid, tap water, sugar solution, salt solution, alcoholic solution, tea, coke, and sweet red wine, was used in turn. The solutions (salt, sugar, and alcoholic solution) were prepared by the student herself, and the process of brewing tea was fully discussed with each of them. A brief discussion concerning the basic ingredients of wine or coke (i.e., young people are not allowed to drink wine or other alcoholic drinks, diabetic people should avoid drinking sweet wine or coke) preceded the distillation of the corresponding water solution.

RESULTS AND DISCUSSION

Heating the water solution

Analysis of the interviews showed that only half of the students believed that liquids expand when heated, but only five of them explained thermal expansion as the result of the molecules moving faster and bouncing further apart. Only these students connected the increase in temperature to the movement of molecules, but none of the students was quite familiar with the idea of temperature as a measure (or a consequence) of the mean kinetic energy of the particles of the liquid. Ten students attributed the expansion of the liquid to the expansion of the molecules themselves.

It was, however, unanimously believed that the liquid will start "evaporating" at a certain temperature, but the temperature will necessarily continue to rise unless we stop heating. They did not develop adequate conceptions concerning the boiling point of chemically pure liquids and its relation to the volatility of liquids. Consequently, the concept of fractional distillation was beyond PST's conceptual grasp. When, for example, the boiling points of water and alcohol were given (100 ^{o}C and 78 ^{o}C, respectively), only two students gave adequate explanations about how the two liquids could be separated by means of distillation making use of the difference in boiling point.

They were also unable to differentiate boiling and evaporation and they could not conceptualize the transformations of energy during boiling or evaporation in general. They could not connect the escaping of molecules from a liquid during boiling to the conversion of a proportion of their kinetic energy (the escaping molecules must have much higher kinetic energy than the average for these in the liquid) into potential energy and, consequently, they were unable to conceptualize the latent heat of evaporation. Only half of the students believed that the steam should lose energy in order to be liquefied, and that the water coming out of the condenser of the apparatus will increase its temperature, because potential energy is being converted into kinetic energy as the liquid is reformed.

The vapors (the steam)

Seven students realized that when a liquid evaporates, only the form of the liquid changes, but not its mass or its basic nature. They understood that the molecules change motion and arrangement and do not change their basic nature, and that during evaporation the outward appearance of a liquid changes, but it is still the same substance. The rest of the students believed that the molecules of the vapor should be different from the molecules of water or the molecules in the water solution. Three of them could not give any explanation for this difference. Six students proposed that water changes into air when it boils, air and vapors being conceived as identical. Air molecules were considered to be of just one kind. This was an indication of their inability to understand boiling as a physical change and the air as a mixture of different gases (or vapors).

Eight more students suggested that boiling is a chemical change where gases of oxygen and hydrogen are produced (8 students). Most of the students proposed that molecules speed up on heating and they tend to move apart, while some students indicated that the size of molecules depends on their temperature (10 students), or that vapors consist of even bigger molecules (4 students), because they continue to expand.

All students understood that in a gas (vapors) the molecules are further apart than those in solids and liquids, and move with high velocities, colliding with one another and with the wall of the vessels containing them. Their motion was described as resembling Brownian motion, that is, they move randomly and irregularly in every direction, but they tend always to go up because gases (and vapors) are lighter and tend to rise. Twenty-five students believed that collisions were not the causes of the change in the direction of movement and were not considered necessary for such a change.

The following answers (A) of a student to questions (Q) raised during the interviews exemplify PST's way of thinking:

> Q. How do the molecules of vapors move? A. *They go up*. Q. So, all of them move upwards. A. *Yes... No, I think that they change direction of movement and move in every direction, but nevertheless they finally go up*. Q. Why do they change direction and how do you think this change happens? A. *This is the way they move, because of their nature*. Q. Do they change direction, let's say, only after a collision occurs? A. *No, I do not think that this is necessary. We learnt in science that the molecules move randomly and irregularly in every direction and that they change the direction of their movement very often*. (The student sketches a movement resembling the Brownian motion as it is depicted in many textbooks.)

Similar ideas were expressed for the vapors of the dissolved substances when students believed that both constituents of the solution would evaporate. For vapors of colored water solutions (tea, red wine, and coke), 14 students believed that "vapors are gases or air which are always colorless or they have color which cannot be seen in the gaseous state, which is invisible matter". Seven students believed that vapors will have the same color as the water solution, and three students believed that the color would be lighter, "because the molecules are further apart". These students were among those who believed that the distillate of tea, red wine, and coke would not be colorless. This idea was one indication that students understood the existence of empty space in matter, at least in the gaseous state.

The distillate

Students were finally asked to compare the properties of the distillate with the properties of the liquid used for distillation, both being at the same temperature. When tap water was used, 4 students insisted that the distillate would be exactly the same as the initial liquid and would have the same density as tap water. These students were unable to realize that tap water was a mixture containing dissolved solids, or that the dissolved solids would remain afterwards to the bottom of the apparatus. Three more students also believed that the distillate would be exactly the same as tap water, but it would have smaller density, because the distance of the molecules would be bigger after distillation. They explained that "heating produced vapors where the molecules are further apart, and, after condensation, it would be impossible to totally eliminate the effects of heating". The explanation resembles the concept of "remanesce" which refers to the variation of magnetic induction of ferromagnetic materials with an applied magnetic field. After a specimen of a ferromagnetic material has become saturated and the magnetic field is reduced to zero, the specimen is still quite strongly magnetized, setting up a flux density which is called remanesce. Similarly, after reducing the temperature, a "remaining expansion" should exist.

The number of students who proposed that the dissolved solid substances in colorless water solutions would remain to the bottom of the distillation apparatus was progressively smaller for salt solution (24 students), sugar solution (19 students), and tap water (17 students). Consequently, the taste of the distillate would not be salty (24 students) or sweet (19 students), or it would have the same salty (3 students) or sweet (6 students) taste, or it would be less salty (3 students) or less sweet (5 students). Even those who proposed that the distillate would not be salty or sweet could not always give adequate explanation.

When colored liquids were used for distillation, the students who believed that the distillate would not have a sweet taste were 17, 14, and 9 for tea, sweet red wine, and coke, respectively. The numbers of students who believed that the distillate would be less sweet were 6, 11, and 8 when tea, sweet red wine, or coke was considered, respectively. For some of these students, the change in taste was not a result of distillation, but rather a consequence of heating or the escaping of gas from coke. The following two excerpts from dialogues during the interviews show that in colored liquids, the cognitive demands were higher, because color was an additional variable, and perceptual experiences concerning colored liquids had an impact on PST's responses.

> Q. You told me earlier that the distillate would be wine again? If you had to select to drink wine either before or after distilling it, which one you would select? A. *I would select to drink the wine, which has not been distilled*. Q. Why, what is the difference? A. *The "distilled wine" would be wine but of different taste, because of heating it*.

> Q. Why do you think that coke will have more sweet taste after distillation? A. *Vapor will escape from it. In case you open a coke and drink it after a while, it is more sweet, because vapor (gas) escape from it*.

When alcoholic solution was considered, 25 students insisted that the distillate "would be the same mixture of water and alcohol". Fifteen of them believed that when mixing water and alcohol a chemical change occurs, and a totally new liquid is formed. Nevertheless, it was clear that their understanding of chemical change was not always correct. Some of the students expressed an "additive" rather than an "interactive" conception of chemical change (Valanides, 2000). For example, some of them insisted that the vapors contain molecules of water and alcohol, which were recombined during condensation to form the new liquid again, but it was not clear whether the breaking apart of water and alcohol molecules was necessary.

When colored liquids were used, the majority of students believed that the distillate would have the same color or that the distillate would have a lighter color. Thus, 17, 19, and 14 students thought that the distillate would have the same color, and 3, 3, and 9 students believed that the color would be the same but lighter when distilling tea, red wine, or coke, respectively. Interestingly, even when the students were sensitized that the color is "added" during the process of brewing tea, students tended to believe that the color becomes an intrinsic and permanent property of a liquid different from water (or "colored water") without being able to give any explanation. Most of them were not sure whether a chemical change occurs during the process of brewing tea, but they felt that the color itself changed the nature of the liquid, which is similar but different from water.

Concerning red wine, students believed that it was related to the nature of the liquid, which is included in red grapes, "because it is impossible to produce red wine from white grapes". None of the students mentioned alcoholic fermentation, and questions related to it were not raised. Students also believed that the color of coke "was chemically added" in the factories, but "once we colored a liquid, a totally new liquid is formed, and it is impossible to obtain a colorless liquid by distilling it." The numbers of students who believed that the color is related to the nature of a liquid were higher than the numbers of students who believed that the taste is also related to the nature of a liquid. These numbers were different for different liquids. Almost all students attributed, however, macro-properties of the materials to the microscopic constituents of matter. They insisted, for example, in their answers (A) to questions (Q) raised by the interviewer that molecules have color that cannot be seen.

> Q. The initial liquid was a colored liquid. You also stated that the vapors would be colorless and, that after condensation, the distillate will have the same or a lighter color. How do you justify these changes? A. *Vapors do have color but it cannot be seen*. Q. But in case the vapors have color why is it you cannot see it? A. *When a substance is colored, its molecules are colored as well. But the molecules are tiny and are not close enough and, thus, you cannot see them. How would you then see their color?*

The students who thought that the color of the distillate would be lighter gave explanations based on the idea of "remaining expansion", which indicates that these students accept the existence of empty space between molecules. Some students believed that a chemical change would occur when dissolving salt (3 students), sugar (10 students), or alcohol (15 students) in water, and that "... the initial materials do not exist any more and a new material with its own properties will be formed". It is thus probable that their conceptions relating to the process and effects of distillation are intertwined with their conceptions relating to the process of dissolving.

CONCLUSIONS

Conceptions revealed from the interviews support the idea that primary student teachers (PST) have limited understanding of the particulate nature of matter and the relation of observable macroscopic changes (i.e., change of phase) with changes in the configuration and energy of molecules, that is, the result of the way molecules move in relation to one another and how they are held together. They face difficulties in understanding the essential changes during chemical transformations of matter, which involve the breaking apart and recombination of molecules, and are unable to differentiate chemical from physical transformations where the structure of molecules is unaffected. They also attribute changes in substances to changes in molecules themselves corroborating with the conclusions of other research studies, where subjects suggested that particles can become hot or cold or even melt (Brooks, Briggs, & Driver, 1984). These results seem to suggest that PST may view the atomic world as an extrapolation of the macroscopic world.

The effects of distillation of a water solution also seem to depend not only on whether PST realize that water contains dissolved solid(s) (i.e., tap water), but also on the nature of the dissolved solid (sugar or salt), or on the nature of the dissolved substances (solid or liquid, colored or colorless solution). Thus, the prevalence of PST's conceptions was progressively greater for salt solution, sugar solution, tap water, mixture of water and alcohol, tea, and coke or wine.

The descriptions of PST's conceptions are intended to arouse awareness and sensitivity concerning the appropriateness and the effectiveness of science teaching at the primary and secondary level. The tenacious nature of students' conceptions should motivate us to design curricular changes and search for more effective teaching sequences and practices. A lot of studies confirmed that learners bring in the classroom conceptions which differ in deeply systematic ways from those accepted by the scientific community. These conceptions are not, however, addressed by traditional instruction and textbooks and, consequently, constitute a significant obstacle to learning. Learners' conceptual framework is usually incompatible with that of the teachers and the textbooks, and, thus, they are not "tuned up" to derive the intended meaning from instruction which is, in general, dominated by a transmissionist point of view considering knowledge as an entity to be transmitted or received.

In contrast, a constructivist view of learning accepts that the individual idiosyncratically constructs knowledge over many years of experiencing the everyday world. The conceptions of learners should not be ignored, but they should be part of the content of teaching. Teaching-learning problems can be overcome by students who are encouraged to be actively engaged in communication than from passive learners who just sit, listen, and respond when the teacher calls them upon. Students' active engagement needs, of course, a relaxed and non-threatening classroom climate and frank exchanges among them and the teacher.

Students should be guided not just to construct new knowledge, but to construct it in the face of strongly held conceptions that guide their thinking and are incompatible with the new knowledge. The teaching strategies should, thus, provide opportunities for students to experience phenomena which run counter to their conceptions for the purpose of inducing conceptual change. Teaching methods and materials addressing students' specific conceptions should be devised, and students should be encouraged to investigate their effectiveness. The process should incorporate the extensive use of discrepant events, discrepant from students' perspective (e.g., demonstrating the evaporation of water solutions containing a solid, or the distillation of colored water solutions) as well as discussions and students' explanations of their observations.

Realization of the discrepancy and the consequent dissatisfaction with an existing conception are, by themselves, far from sufficient to cause conceptual change. They constitute, however, an important aspect of effective teaching for conceptual reorganization of the learners' internal structures, which determine to a large extent the kind of sensory inputs (selective attention) and their consequent processing. The fact that certain conceptions are not changed in the course of traditional instruction may be due to the failure of instruction to disequilibrate students with respect to their own conceptions. Conceptual change cannot be accomplished without causing disequilibration, which usually occurs when an expected event does not occur and the learner's expectations are not met. The acceptance of a new conception is not, of course, automatic but it depends on its intelligibility, plausibility, and fruitfulness (Gunstone, Gray, & Searle, 1992). These criteria are not easily achieved, but they are closely interwoven with learners' involvement and control of the teaching-learning environment.

University schools of education need to devote continuous efforts to train prospective teachers in conceptual-change teaching techniques. Consequently, prospective teachers should be encouraged, by one way or another, to expose and articulate openly their conceptions about the physical world. Such efforts will make them aware of the elements of their own conceptions and will facilitate the search for teaching interventions conducive to their conceptual development. Prospective teachers should not only be acquainted with the constructivist point of view of learning, but they should also be equipped with the necessary capabilities of continuously identifying their students' conceptions and implementing teaching approaches that promote conceptual understanding among their students. The scarcity of teachers trained in, or being aware of, conceptual change approaches speaks strongly about the urgent need to design and implement workshops and in-service materials that can inform and stimulate interest in conceptual-change teaching. In-service education should also sensitize teachers about the need to search for their own students' conceptions and teaching practices which would support or even accelerate children's conceptual growth.

The author employs in his teaching a conceptual change approach and he, furthermore, started developing teaching materials appropriate both for pre-service and in-service training of teachers. The effort aspires to contribute to a growing body of research concerned with the design, development, and implementation of curriculum materials and instructional strategies built around aspects of learners' cognition (conceptions). These approaches seem to promote metacognitive awareness and trigger interest in learning which, in turn, facilitate learners' cognitive engagement and conceptual understanding. In the present effort, there were powerful indications of metacognitive behavior and motivation for learning, which might be related to perceived fruitfulness. The subjects were not far away from teaching the concepts with which they were grappling and most of them insisted, during or after the interview, on raising questions concerning, for example, the taste and the color of distillate, indicating that the interview process forced them to think in a quite different way and aroused their interest about the process and effects of distillation.

The existing range of examples of conceptual change approaches (Anderson & Smith, 1987; Driver, 1988; Driver & Oldham, 1986; Dykstra, Boyle, & Monarch, 1992; Lee et al., 1993), and the instructional techniques which seem to be conducive to conceptual change pave a promising direction for effective instruction and conceptual understanding in science. The results are so far inconclusive, and efforts towards this objective need to be coordinated and intensified.

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