From the Scientific to the Educational: Using Monte Carlo Simulations of the Microkosmos for Science Education by Inquiry

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Introduction

The application of the "microkosmos model" in education, widely known as "particulate nature of matter," has been accepted in some cases while rejected in others, by researchers. To begin with, Nobel Prize laureate R. Feynman (1995) praises the contribution of the particle model in science and specifically in understanding the macrokosmos (or macrocosmos) through the microcosmos. Other researchers support that understanding particulate nature of matter is of great importance for students so as they may approach all branches of science (Bouwman-Gearhart et al. 2009). Wiser and Smith (2008) insist on students learning about particles as early in their education as possible (more specifically, at the end of primary school or at junior high school) because this helps them solidify their first understanding of matter and also provides an important base for the understanding of several macroscopic concepts, which are difficult to be approached in any other way but through the atomic molecular theory. The learning of the particulate nature of matter is useful, as well, in cases of working with phenomena where students lack observational data, like the case of invisible gases (Löfgren and Helldén 2009; Papageorgiou et al. 2010).

According to Chabay and Sherwood (1999), in the case of high-school students, focusing on the fact that matter is composed of atoms, as well as on the process of modeling physical systems, is more interesting and relevant to them than a repetition of a purely classical approach. In addition, Snir et al. (2003) demonstrated that students who understand how the properties of atoms and of molecules explain macroscopic phenomena, had also understood well, from a macroscopic perspective, the

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basic characteristics of matter (weight, volume, density). In a study with students of late primary or early high school, Hwang (2000) found that the conception of the particle model is evolving gradually at these ages. Furthermore, it was concluded that particulate nature of matter is one of the fundamental models of science.

Understanding the particulate model can be difficult for elementary and even secondary school students. Franco and Taber (2009) investigated the results of the application of a curriculum context, where "particles" was a key idea in the science courses for all 11–14-year-olds in the United Kingdom. The result of this study showed that only a minority of students had understood the basic particle theory at the end of this long course sequence. In the same direction, Löfgren and Helldén (2009) admit that their aim for teaching the particulate nature of matter was so that those students who wished could use particle models when considering changes in matter. In the case of university students, Thacker et al. (1999) found that most of the students whose instructional experiences included an emphasis on the development of models of microscopic processes developed a better understanding of the phenomena studied.

Many researchers agree that the early development of a simple particle model may – eventually – help students conceive a more complex subatomic particle model (Bouwman-Gearhart et al. 2009), since the understanding of a basic particle model by the students is necessary for them in order to approach the atomic structure, taught later (Papageorgiou and Johnson 2005, 2010). According to Eshach and Fried (2005), science taught in early school years is an effective frame for the development of scientific thought and is expected to contribute to the foundation of understanding difficult science concepts and phenomena, which will be studied later on in a more formal way.

In the case of Greece, after a special edition of the "Educational Model of Microkosmos" had been incorporated in the official handbooks for primary school pupils of 10–12 years old (Apostolakis et al. 2006), researchers investigated the influence that enhancing the teaching process with activities supported by information technologies had on teachers and pupils (Imvrioti 2011; Tzimos 2011). The results show that this model is appropriate for primary education, in the sense that microcosmos helps understand the macrocosmos, while understanding is improved by proper software. Other researchers' investigations of junior high-school students' understanding (Tsitisipis et al. 2011) or secondary and university students' comprehension (Stefani and Tsaparlis 2009; Tsaparlis and Papaphotis 2002, 2009; Tsaparlis 1997; Vlahou et al. 2011) of the particulate nature of matter indicate the interest of the researchers on this subject, while their propositions are expected to improve teaching interventions and learning difficulties or to be useful in designing programs of studies.

Undoubtedly, further investigation is necessary in order to determine how to support students from their early school life in order to enable them to build a particle model by the age of 16 and be capable of applying it when explaining real, everyday situations (Löfgren and Helldén 2009).

We made the hypothesis that the understanding of the processes of microcosmos and the educational use of the model of microcosmos can be enhanced by the implementation of educational simulations, visualizations, and animations. In this chapter, we report results of an educational study that provided some support for this hypothesis.

Framework, Questions, Aims, and Research

The general framework of this research is to notice that science education aims merely at knowledge of phenomena and definition of concepts, while there is no important focus neither on the procedures which caused or led to these phenomena nor on the deeper understanding of these procedures. This kind of science education results not only to a superficial view of the natural world but also to the impression that science is fragmentary. In addition, it certainly does not provide any satisfactory link between science and science education, that is, it does not join scientific research with educational process in any of their basic characteristics: subject, methodology, and supporting software. On the contrary, we believe that nowadays science education should directly take advantage both of the scientific research results and of the methodology and supporting software that the research utilizes. More specifically, we support that education ought to take into account scientific findings about the structure, interactions, and motion of particles, as they are expressed by the "microcosmos model" of contemporary science, in order to explain with this knowledge of the microcosmos processes the physical, chemical, and biological phenomena of the macrocosmos. Furthermore, the use of the microcosmos model and microscopic explanations could unify the fragmentary view of science.

Our research questions are whether, and up to which degree, teachers, students, and pupils understand and use the microscopic model, after they have been taught about it through the scientific/educational methodology and by the use of educational software containing simulations and visualizations of that model.

The answers to these questions will help us to achieve three aims: first, the transfer of knowledge of microcosmos procedures from science to education, which is declared by science as a "scientific microcosmos model" and has been transformed by education to a "scientific/educational microcosmos model"; second, the configuration and application of the scientific research methodology to the "scientific/educational methodology by inquiry," which may be used at the educational procedure of science; third, the utilization of contemporary digital technologies both at the level of scientific research and that of educational procedure.

Our research included the following stages: (a) We began by modifying the scientific microcosmos model, and, thus, the microscopic structures, interactions, and motions are likely to be comprehended by students (of any level); (b) we then transformed the basic steps of scientific methodology to be feasible by students for science education; (c) we copied ideas and techniques of the microcosmos simulation and visualization from the scientific research and developed a dynamic educational software and static captures in order to offer students a visual simulation of the structure, interactions, and motion of the microkosmos particles; (d) we implemented the above software (and/or static captures) into the steps of "scientific/educational by inquiry methodology" during the educational procedure of all levels (primary, secondary, university, in-service teachers' training) so that students may be able to explain macroscopic phenomena by microcosmos processes; and (e) we evaluated this implementation.

From Scientific to Educational Simulations

For the educational simulations of the microcosmos, we used the Monte Carlo methods, which have been used with great success in elementary particle research. These statistical methods use sequences of random numbers to perform various calculations to simulate stochastic systems like "microcosmos." The structure, the interactions, and the movements of microcosmos – from the "a-toma"/superstrings (?) to molecules – are simulated and animated by a hands-on computer program, with the use of Monte Carlo methods and techniques since microcosmos is eminently a stochastic system. The used Monte Carlo techniques employ those methods in order to simulate and animate, by means of a computer, certain stochastic processes according to specific distributions (Kalkanis 1996, 1997). This way, the stochastic processes of microcosmos may contribute to explaining and predicting (the) phenomena of macrocosmos.

In science, Monte Carlo techniques have proven to be a powerful and irreplaceable tool for research, mainly in predicting and/or explaining experimental data (for a typical example, see Phillips et al. 1984; Kalkanis 1984).

In education, we may profit by the features of simulations and visualizations of the microcosmos too. These simulations and visualizations may offer a glimpse, even a view, of the details of the complex realistic systems operation of microcosmos with a pedagogical virtue. Furthermore, this characteristic of Monte Carlo simulation and animation programs is one of the characteristics which "legitimate" the use of computers in science education (Hadzidaki et al. 1998; Kalkanis and Sarris 1999).

On the other hand, microcosmos is the part of the world where the wave–particle duality comes up vigorously, and such computer simulations/animations may wipe out the impression or misconception, generally held by students, that "quantum mechanics is simply incomprehensible" and clarify some quantum "paradoxes" such as the paradox of wave–particle duality. In the animation program, designed and created in situ (Dimopoulos and Kalkanis 2003, 2004a, b, 2005, 2006, see simulations in http://micro-kosmos.uoa.gr (english version) → Science Education), the wave–particles are visualized by successive appearing and disappearing dots, without any display of track.

A relevant research (Drolapas and Kalkanis 2011) confirmed that the understanding of microscopic particles by students and teachers is better achieved when particles are shown with their interior structure, instead of particles bound by circles. Such images of atoms and molecules not bound by circles, that do not exist in any case, are shown in Fig. 1.

An imaginary journey into the interior of the matter offers students (and teachers) a glimpse of the microcosmos processes, which can then help to explain many

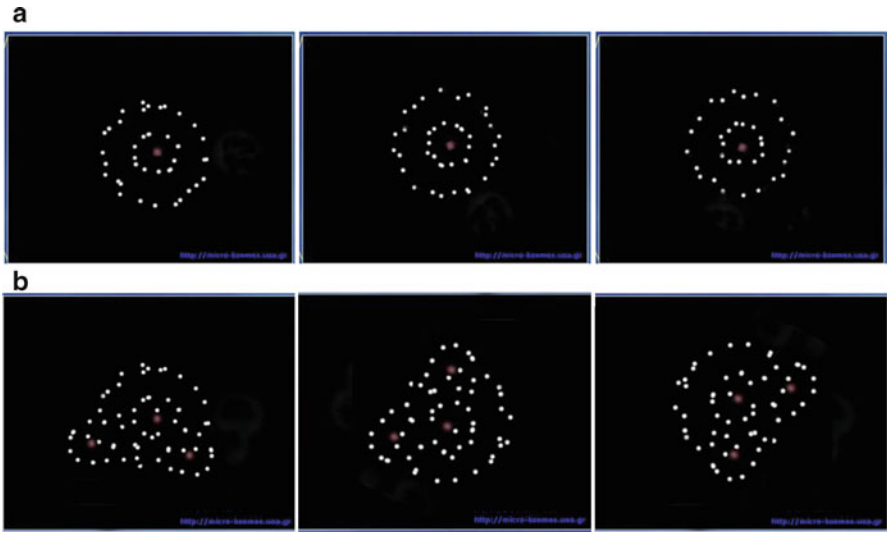


Fig. 1 (**a**) The wave–particles/electrons of an atom are shown in three successive captures of the atom, without any electron tracks and atom boundary. (**b**) Captures of a water molecule where its interior atomic structure is shown without any electron tracks and without any molecule boundary

macroscopic concepts and phenomena (e.g., excitation–relaxation of atom's electrons, emission of photons, molecules' interactions, rigidity of solids, molecules' thermal motion, expansion–contraction of matter, fluidity of liquids and gases, static pressure, and friction). The hands-on operation of an improved version of this computer simulation and animation program may offer the opportunity to students and teachers alike to change or select the parameters of the desired views of the microscopic processes (number of wave–particles, interactions, motion…) in order to correspond to certain macroscopic phenomena.

The dynamic educational simulations and visualizations of the microcosmos created with Monte Carlo techniques (at the Laboratory of Science, Technology, and Environment of the Department of Primary Education of the University of Athens) have been intergraded into independent digital presentations of normative, exemplary educational procedures and/or independent educational software for students of all grades and forms of education, as well as into episodes of educational television (Kalkanis et al. 2007). An example of this software is presented in Fig. 2, which display captures of the position and movement of molecules in solids, liquids, and gases, at two different temperatures.

As a consequence, the phenomenon of expansion of solids, liquids, and gases and the phenomenon of change of state from solid to liquid and to gas, when temperature rises, are explained. Other microscopic procedures that have been simulated or visualized in the frame of this scientific/educational research are the movements of the free electrons of a metal with or without electrical current. These movements explain not only the electrical current but also thermal and optical secondary phenomena.

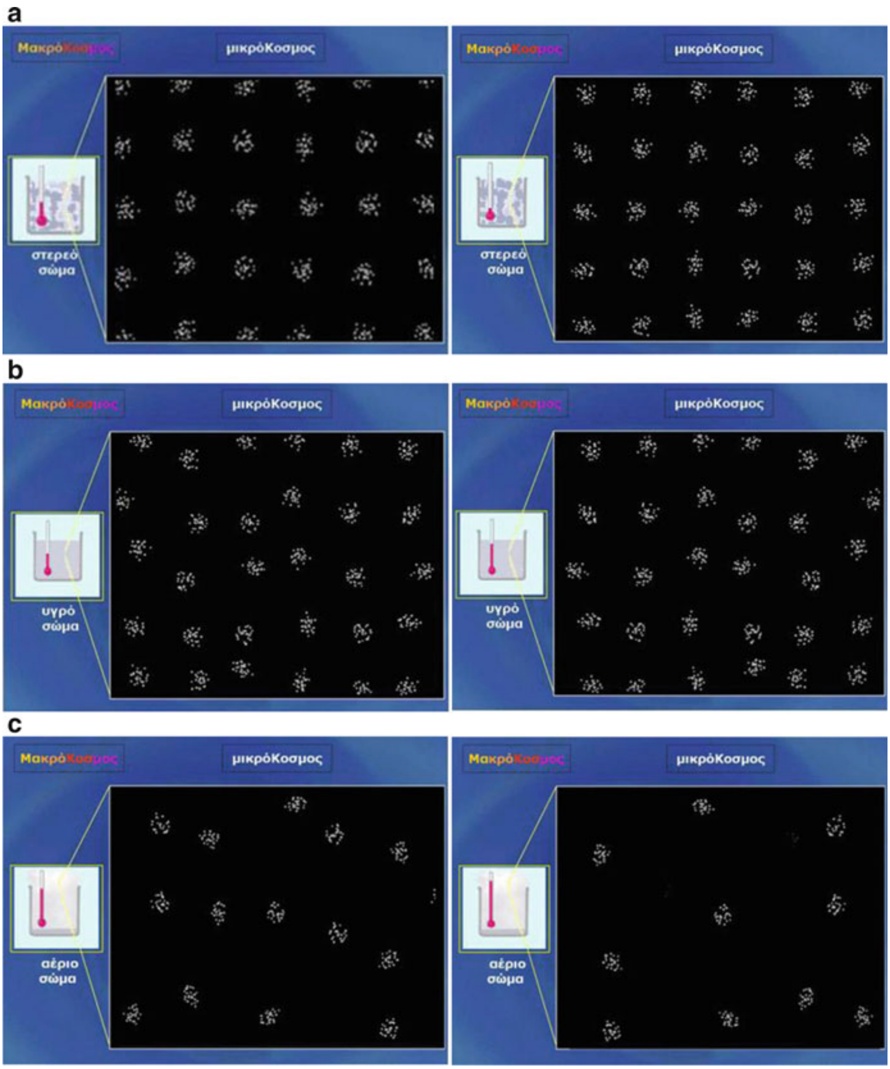


Fig. 2 (**a**) Captures of the dynamic simulations/visualizations of the positions and of movements of the molecules in a solid at two different temperatures. (**b**) Captures of the dynamic simulations/visualizations of the positions and of movements of the molecules in a liquid at two different temperatures. (**c**) Captures of the dynamic simulations/visualizations of the positions and of movements of the molecules in a gas at two different temperatures

Static pictures from these dynamic simulations/visualizations, like those depicted in Fig. 3, have been included in the official science handbooks that are published by the Greek Ministry of Education and are taught to students of the last two grades of primary education (Apostolakis et al. 2006, see http://micro-kosmos.uoa.gr (english version) → Science Education).

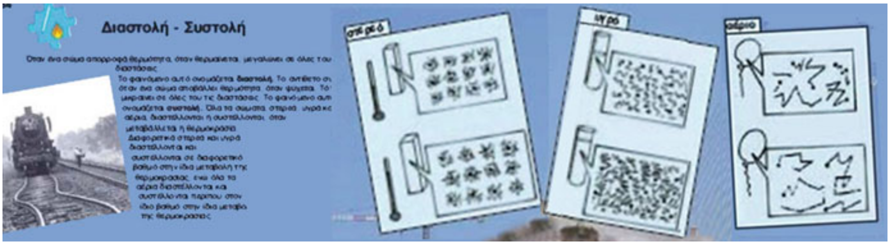


Fig. 3 The microscopic movements of the molecules of a solid, a liquid, and a gas are depicted at two different temperatures. These sketches explain the phenomenon of expansion of solids, liquids, and gases and consequentially the phenomenon of change of state, from solid to liquid and to gas when temperature rises

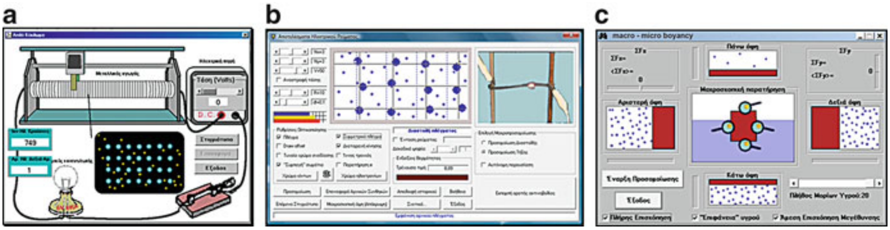


Fig. 4 (**a**–**c**) Captures of dynamic simulations/visualizations of microcosmos vs. macrocosmos

Figure 4 shows three examples of the relation of microscopic particles' movement to the corresponding macroscopic experiments, as presented by some dynamic simulations and visualizations of the microcosmos, which have been designed and created in situ as well (Kyriaki 1997; Tsakonas and Kalkanis 1998; Tsakonas et al. 2011; see simulations in http://micro-kosmos.uoa.gr (english version) → Science Education).

Figure 4a shows the thermal movements of free electrons and positive ions in a metallic conductor, with or without electrical current, along with simultaneous measurements of macroscopic physical quantities of the applied voltage and the current flow. At the same time, the number of collisions of free electrons, moving in all directions of the conductor along with the ions of the metallic conductor, is calculated and is compared with the values and the direction of current. The next figure (Fig. 4b) shows the changes of movements of electrons and ions of the metallic conductor, when current changes. These changes are combined with the macroscopic changes of the conductor, such as the change of temperature, the change of its length due to thermal expansion, and the change of state from solid to liquid, when temperature rises significantly. The last figure (Fig. 4c) shows the movement of air and liquid molecules around a solid, which is half-immersed in the liquid. The molecular collisions with the surface of the solid are then counted, and the static pressures and buoyancy force are calculated, from the macroscopic forces applied to the solid by the air and liquid on every surface.

The use of dynamic simulations instead of static captures of microcosmos is preferred by teachers, students, and pupils; however, we believe that both should be available and utilized during any educational procedure, since in some cases, systematically or occasionally, the use of digital technologies is not easy or possible.

From Scientific to Educational Methodology: The Research Study

The dynamic simulations and visualizations of the microscopic processes, as well as the static captures or sketches, have been integrated into the steps of scientific/educational method by inquiry. We formatted the scientific method of research into five simple and explicit steps: (a) trigger of interest, (b) hypotheses, (c) experimentation, (d) theory, and (e) continuous testing. We then adjusted each of them for students as steps of an educational method by inquiry for the educational procedure: (a) trigger of interest; (b) hypotheses; (c) experimentation; (d) conclusions, applications; (e) generalizations, explanation with microcosmos (Straga and Kalkanis 1999; Kalkanis 2007).

This scientific method was formatted by Newton; however, it originates from the ideas of Thales of Miletus, which were also used by other natural philosophers and early scientists in ancient Greece, for example, by Archimedes (Lloyd 1970). This method has been used since the ancient Greek philosophy era, and it is still used nowadays, in the context of modern science. It is believed that this scientific method not only helps the scientific research to be efficient and fruitful but also discriminates sciences from other fields of knowledge. To give an example of the use of this method in a modern scientific research and the way in which the various phases of the research were integrated into the five steps of this methodology, as described above, we can refer again to the procedure followed during the aforementioned study about proton decay, using the Harvard–Purdue–Wisconsin detector.

The scientific/educational by inquiry method, formatted into the five simple steps mentioned above, is used by all Greek students of 5th and 6th grade of primary education in science, in accordance with the official science handbook compiled by the Ministry of Education, as well as the in-service retrained and future teachers who studied at the University of Athens. During this research, we also integrated the educational simulations/visualizations of microcosmos into the steps of this methodology.

As an example of the employment of this scientific/educational method and the way in which we expect students to integrate the various processes into the five steps of the methodology, we present the worksheet for the topic "expansion/compression of matter" vs. "increase/decrease of temperature".

Applications, Results, and Evaluation

The study was carried out by the Laboratory of Science, Technology, and Environment of the Department of Primary Education of the University of Athens during the academic years 2006–2010. There were three groups of participants:

(a) 200 in-service teachers, 84 of them receiving in-service training at the Marasleio Didaskaleio of the Department of Primary Education taking compulsory theoretical courses and practical teaching exercises at the Science Laboratory, as well as 116 teachers taking training seminars at Peripheral Educational Centers in Attica and in schools by school counselors.
(b) 600 undergraduate (2nd and 3rd year) university students of the Department of Primary Education taking compulsory theoretical courses and compulsory experimental exercises at the Laboratory of Science.
(c) 300 fifth-grade primary education pupils (10–11 years old) in science classes, before being taught the relevant phenomena.

All participants spent (in their usual classroom) 4 h on selected thematic units performing (in groups of three) experiments concerning materials' expansion/compression as well as change of state, watching and interacting with the relevant educational software, completing worksheets, and recording their observations. The experiments were performed by the participants themselves, and the role of instructors was purely supportive. The educational process was organized according to the aforementioned steps of the scientific/educational methodology by inquiry. An example of the worksheets and experiments is shown in Fig. 5.

Written questionnaires were given to the participants before and after the 4-h intervention, and the participants' worksheets were then analyzed. The questionnaires included questions about the following: (a) the explanation of macroscopic properties (volume, shape, and rigidity or viscosity) of materials, based on the position and micro-movements of their particles/molecules; (b) the explanation of the change of dimensions (expansion or compression) of solids, liquids, and gases; and (c) the explanation of the change of state of the materials (to or from solid, liquid, and gas) when the temperature changes, which was also based on the micro-movements of their particles (molecules).

The participants' (teachers, students, pupils) performance was characterized as "inadequate" (when answering adequately less than half of the questions), "adequate" (when answering adequately more than half of the questions), "complete" (when answering adequately all the questions), and "excellent" (when answering completely all the questions providing the correct microscopic explanations). After defining these marking criteria, three graders evaluated the participants' answers without knowing which group the participants belonged to or whether they were completed before or after the intervention.

The results (expressed as percentages) in all three categories of responses, before and after the educational process, are presented in bar diagrams form in Figs. 6, 7, and 8.

Focusing on the category of "inadequate": performance (less than 50 % of correct answers), we notice that the great majority of teachers had less than 35 % of correct answers, of students less than 22 %, and of pupils less than 13 %.

The participants' performance was marked as 1 when it was "inadequate," 2 when it was "adequate," 3 when it was "complete," and 4 when it was "excellent." The scores of participants pretests and posttests in each case (teachers, students, and pupils) were subjected to paired-samples *t*-test, which showed statistically significant differences ($p<0.001$) between pre- and posttest scores in each case, in favor of the latter.

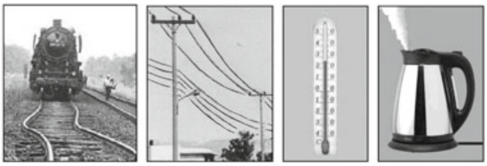
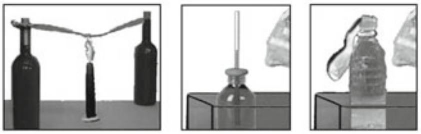
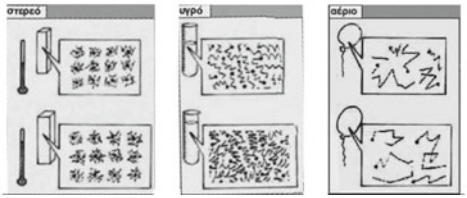
Trigger of interest	Observe these pictures, describe the phenomena and correlate the dimensions of some materials with the temperature 
Hypothesis	Hypothesize about the correlation of materials' dimension and temperature and explain the phenomena (A typical and usual explanation): "*I believe this happens because the volume of the molecules that make the material increases when the material is heated*" 
Experimentation	Perform experiments of heating and cooling different materials (solids, liquids, gasses) and observe carefully what happens 
Conclusions – applications	Derive conclusions from your observations about the heating/cooling of a material vs. its expansion/compression, and apply the findings to the phenomena used for triggering and explain them (An expected conclusion): "*I conclude that the heating/cooling of a material causes its expansion/compression, however, despite the detailed observation of the experimental process, I cannot make any conclusion regarding the cause of a material's expansion/compression with increase/decrease of the temperature and confirm or reject any hypothesis …*"
Generalization – explanation with micro-cosmos	Watch carefully relevant static captures, like those depicted below (and/or relevant dynamic simulations/visualizations like those shown in Fig. 2a, b, c)  (An expected explanation): "*The expansion/compression is based not on the change of the volume of molecules but on the increase/decrease of movement of molecules (consequently, they fend off/approach each other)*"

Fig. 5 Worksheet for the topic "expansion/compression of matter" vs. "increase/decrease of temperature"

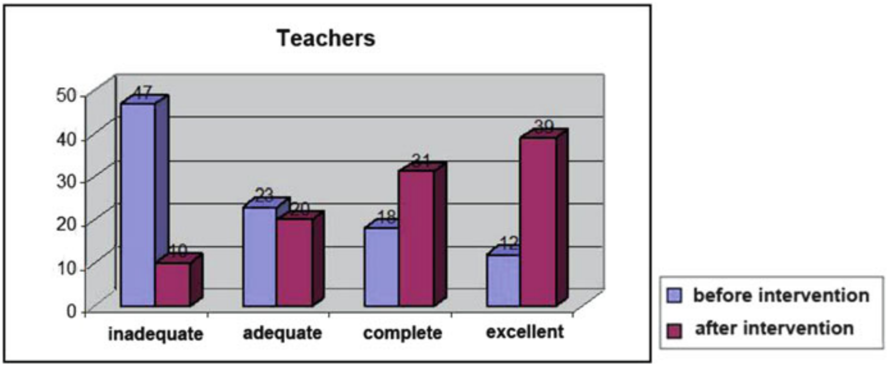


Fig. 6 The percentages of teachers' responses, before and after the educational process

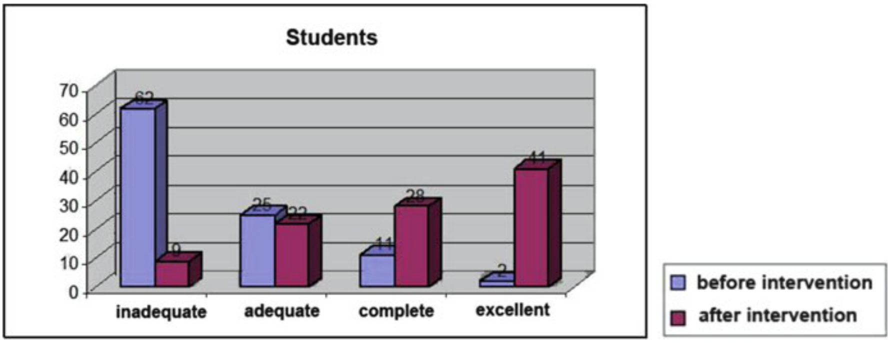


Fig. 7 The percentages of students' responses, before and after the educational process

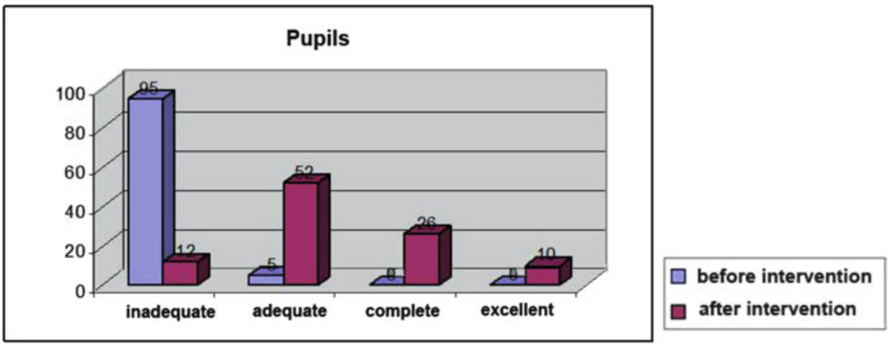


Fig. 8 The percentages of pupils' responses, before and after the educational process

Teachers: $t(199) = -21.211$; $p < 0.001$ (means: pretest =1.95/4 and posttest = 2.99/4, std. deviations: pretest =1.065 and posttest = 0.997).
Students: $t(599) = -49.774$; $p < 0.001$ (means: pretest =1.53/4 and posttest = 3.01, std. deviations: pretest =0.768 and posttest = 0.996).
Pupils: $t(299) = -30.190$; $p < 0.001$ (means: pretest =1.05/4 and posttest = 2.34/4, std. deviations: pretest = 0.218 and posttest = 0.816).

These *t*-test results prove the effectiveness of the intervention in all categories of participants.

Conclusions and Implications

We think that the above results of the evaluation are (at least) encouraging, and we suggest the generalization of creating such educational software covering more areas of science as well as broadening its use to more teachers, students, and pupils.

Based on the questionnaires, both teachers and university students understood the particulate structure of matter, correlating the microscopic processes with macroscopic phenomena. In addition, according to their comments in the worksheets, they felt confident that they could use the microcosmos model to explain macroscopic phenomena to their pupils (76 % of teachers and 54 % of university students/prospective teachers).

The elementary school pupils understand the particulate nature of matter less well but made efforts to connect the microscopic processes with the macroscopic phenomena, providing in some cases explanations where macroscopic properties and microscopic processes were confused. We are of the opinion that the results reflect mostly the use of the software. In the case of material and software, the instructors did not encounter any such difficulties in the implementation process. Moreover, in regard to material, software, methodology, and structure of the program, the research confirmed the feasibility and effectiveness of their application, since the participants' performance was improved significantly after the intervention, as shown by the above statistical analysis.

Therefore, we suggest the continuation and generalization of the application of this kind of programs, with additional information, material, software, and processes, especially with processes that are both attractive to and effective on pupils. This will lead to the optimization of the educational and instructive role of the microscopic model, which not only extends science education to contemporary scientific theories but also contributes to a deeper comprehension and interpretation of physical phenomena of everyday life.

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