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LEARNING

Micro–macro compatibility: When does a complex systems approach strongly benefit science learning?

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Abstract

The study explores how a complexity approach empowers science learning. A complexity approach represents systems as many interacting entities. The construct of micro–macro compatibility is introduced, the degree of similarity between behaviors at the micro- and macro-levels of the system. Seventh-grade students' learning about gases was studied using questionnaires and interviews. An experimental group ($n = 47$) learned with a complexity curriculum that included agent-based computer models, a workbook, class discussions, and laboratory experiments. A comparison group ($n = 45$) learned with a normative curriculum, incorporating lectures, a textbook, class discussions, and laboratory experiments. Significant learning gains and strong effect sizes were found in the experimental group's overall learning. Diffusion, density, and kinetic molecular theory were learned better with a complexity approach. Pressure, temperature, and the gas laws were learned similarly with both approaches. Learning to notice micro-level behaviors and their probabilistic nature was greater with the complexity approach. Analysis showed that only concepts that have less "micro–macro compatibility" were learned better with a complexity approach. Thus, a complexity approach helps separate the microbehaviors and then relate them to the macrobehaviors when these behaviors are dissimilar. We discuss how micro–macro compatibility helps point to concepts whose learning would benefit strongly from a complexity approach.

KEYWORDS

agent-based modeling, complex systems, conceptual learning, science education, systems thinking

1 | INTRODUCTION

Understanding the structure of matter and its properties is central to our everyday knowledge of many phenomena and our ability to address vital engineering and science challenges. Although much effort has been expended in teaching these topics in schools, many students exhibit some difficulty in understanding chemical systems (Adadan, Irving, & Trundle, 2009; Ben-Zvi, Eylon, & Silberstein, 1986; Dori & Hameiri, 2003; Johnstone, 1991; Nakhleh, 1992; Nussbaum, 1985; Ozmen, 2011; Plass et al., 2012; Sevian, Talanquer, Bulte, Stacy, & Claesgens, 2014; Talanquer, 2007; Treagust, Chittleborough, & Mamiala, 2003). For example, a variety of alternative notions about gases include ordered packing and weightlessness (Lin, Cheng, & Lawrenz, 2000; Mas & Perez, 1987; Nussbaum, 1985; Stavy, 1988). Students' main sources of difficulty in understanding these concepts concern the small scale at which the submicroscopic world, the causal substrate, operates and the systemic nature of such phenomena (Gilbert & Boulter, 2000; Johnstone, 1993; Levy & Wilensky, 2009a). One commonality between many of these misunderstandings has to do with distinguishing clearly between the micro- and macro-levels in the chemical system.

Complexity approaches to learning about systems have come into the limelight in several different domains of science and education. Such approaches (also known as agent-based modeling, or ABM) are based on the following idea: A system can be represented as many entities that operate according to a small set of simple rules. For example, ant convoys can be seen as resulting from interactions between single ants, food sources, and pheromones. Emergence is a central concept associated with complexity and is the process by which the actions and interactions of the system's entities emerge into global patterns (Bar-Yam, 1997; Holland, 1995; Kauffman, 1995). In the ant example, an ant who has found food releases pheromones that evaporate. Other ants seek out pheromones, heading for the strongest scent. The actions of many individual ants can reach a critical mass which results in a path of pooled scent, along which we can see an ant convoy marching. This complexity approach ties in with the recently published U.S. framework for science education (National Research Council, 2012) that underscores systems and system models as one of the central crosscutting learning concepts.

A complexity approach encourages causal thinking in connecting individual behaviors with systemic patterns. Using this approach, students are able to understand the mechanisms driving these patterns (Levy & Wilensky, 2008; Dickes, Sengupta, Farris, & Basu, 2016). Learning through this approach focuses on entities and their actions, such as movement, interactions, and global flows and allows students to comprehend parallel processes by which emergent phenomena form. Finally, this approach provides a general framework that addresses the need to connect between different systemic phenomena (Goldstone & Wilensky, 2008). Several studies have reported on the particular benefits of a complexity approach toward improving student learning in chemistry (Levy & Wilensky, 2009b; Dickes et al., 2016; Holbert & Wilensky, 2014).

In contrast to a complexity approach to learning concepts, the currently widely used and established normative approach to scientific systems is usually not based on bottom-up representations but rather tends to focus on states rather than processes (Chen & Stroup, 1993; Perkins & Grotzer, 2005). In learning about systems, the normative approach lacks a coherent common framework (Goldstone & Wilensky, 2008) and is learned in a sequential way (e.g., input–process–output structures) rather than providing a basis for emergent causality which operates in a parallel fashion (Chi, 2005).

In this study, our research question was: how does a complexity approach, which highlights micro-to-macro transitions, empower science learning? We addressed this question by comparing concepts that are learned with a complexity approach with those that are learned using a normative approach. With respect to previous research into science conceptual learning with a complexity approach, we use a more fine-tuned analysis of the concepts learned. This helps us separate between concepts that are learned similarly with a complexity and a normative approach, and concepts for which a complexity approach may advance learning to a greater extent. Thus, the aim of the study was to detect specific advantages and disadvantages of learning chemistry through a complexity approach, thereby enabling a better understanding of when such a perspective can be beneficial for learning.

2 | LITERATURE REVIEW

The particulate structure of matter is one of the most fundamental concepts in science studies and is the basis on which many other scientific concepts are understood. In chemistry, these concepts include material properties, phase changes, and chemical reactions (Margel, Eylon, & Scherz, 2008). Research consistently shows that many students find it difficult to understand the particulate structure of matter (Dori & Hameiri, 2003; Johnstone, 1991; Nussbaum, 1985). Many students in the initial stages of learning hold a view of matter as continuous (whereby the material is perceived as a continuous structure) and later construct a hybrid model that combines features of both continuous and particulate structures (whereby the material is made up of tiny particles in a vacuum) (Renström, Andersson, & Marton, 1990; Talanquer, 2007). Most high school students believe that gas is composed of tiny particles invisible to the eye, yet they attribute macro-level phenomena to particles, such as color and density (Nussbum, 1985). Johnstone (1991) defined three levels of representation required for a proper understanding of scientific concepts: (1) The “macroscopic” level, which refers to the phenomena that can be received through the senses; (2) the “microscopic” level, which depicts the particle level; and (3) the “symbolic” level, which refers to processes and states that are represented by formulae and chemical equations. There is plenty of evidence indicating that chemistry students have difficulty understanding and using these three levels of representation (Gilbert & Treagust, 2009). This may be attributed to a lack of deep understanding of the nature of the submicroscopic world (Gilbert & Boulter, 2000; Harrison & Treagust, 2002; Wright, 2003), incomprehension of the basic rules at the symbolic level (Marais & Jordaan, 2000), and an inability to make transitions between the three levels (Gabel, 1994, 1987).

Emergence is a process that connects the first and second levels in Johnstone’s model and describes how micro-level interactions result in macro-level patterns. To understand emergence, it is necessary to observe at least two levels: the micro- and macro-level. The micro-level refers to items that comprise the system, and the macro-level refers to the entire system features (Wilensky, 1999). Additionally, a holistic view of the system needs to be *distinguished* from a local view of the participating entities and their interactions. Noticing such interactions helps animate the system, allowing students to perceive the system as *dynamic*. Indeed, Luisi (2002) found that in understanding chemical systems, students tend to focus on individual static components without noticing interactions and thus they lack a dynamic view. Furthermore, students that assign macro-level properties and processes to particles or molecules, so that a change in color or volume is perceived as happening also at the molecular level (Barke, Hazari, & Yitbarek, 2009; Kind, 2004; Nakhleh, 1992; Taber, 2002). This makes it difficult for them to understand emergent processes, as molecules and bulk matter are not well-distinguished and the system lacks a dynamic quality. This failure to understand the distinction between micro- and macro-levels has been evidenced by studies exploring the complexity view in learning chemistry (Rappoport & Ashkenazi 2008; Stains, & Sevian, 2015; Talanquer, 2008, 2015; Tümay, 2016a). Rappoport and Ashkenazi (2008) interviewed three groups of participants: students in the first stages of their undergraduate chemistry studies, more experienced students, and chemistry faculty researchers, and asked them questions regarding their comprehension of pressure, heat, and temperature concepts in chemistry. They found that the faculty researchers correctly conceived the system’s properties as resulting from interactions between micro-level entities. However, most of the students could not connect between phenomena at the two description levels and assigned properties belonging to the bulk system to the molecular level. Other studies have shown a similar picture. Stains and Sevian (2015) explored eighth-grade students’ understanding of how perfume diffuses in a room, how its spread changes with temperature and how having two gases mix impacts the process. They found that only 10% of the students understood diffusion as emergent. Furthermore, Talanquer’s (2008) investigation into undergraduate students’ explanations of observed phenomena (color, smell, and taste) showed that most of the students used an additive (noninteracting) heuristic method rather than an emergent process. Finally, Tumay (2016a) explored undergraduate chemistry students’ understanding of acids that were studied via a normative curriculum, through a complexity perspective. They found that students could only use a small number of factors to explain their reasoning, and they did not address the dynamics of the process. These findings resulted in Talanquer (2015) pointing out that emergent processes need to be part of the basic strata in learning chemistry, and further research is needed to make fundamental changes in how chemistry learning materials are designed. Similarly, Tumay (2016b) has also proposed that understanding emergence is critical to constructing the epistemology and ontology that supports a deeper understanding of chemistry.

The specific contribution of a complexity approach lies in the way it helps students decipher interactions among the micro-level entities and their stochastic behaviors and thus comprehend the macro-level as more than the "sum of its parts" (Epstein, 2006; Goldstone & Janssen, 2005; Wilensky, 1999). Thus, the complexity approach is best suited for studying emergent chemical systems and has the potential for students to develop a general understanding of complex systems (Goldstone & Wilensky, 2008). Whereas, the normative approach focuses on individual scientific phenomena without emphasizing their systemic properties. In the current study, there was no specifically expressed provision of systems concepts, but rather a special scaffolding (consisting of computer models, a workbook, and presentation of scientific phenomena), which directed the students to a systems observation of the studied phenomena. Several earlier designs for learning science with a complex systems perspective usually implemented the computational ABM approach, which encourages causal reasoning and leads to an understanding of the mechanisms underlying the phenomena (Levy & Wilensky, 2008). Such designs have demonstrated important advantages to learning through a complexity approach (in chemistry: Holbert & Wilensky, 2014; Levy & Wilensky, 2009b; Stieff & Wilensky, 2003; Wilensky, 2003; in physics: Brady, Holbert, Soylu, Novak, & Wilensky, 2015; Sengupta & Wilensky, 2009; in biology: Dickes et al., 2016; van Mil, Boerwinkel, & Waarlo, 2013; Van Mil, Postma, Boerwinkel, Klaassen, & Waarlo, 2016; Wilensky & Reisman, 2006; Wilkerson-Jerde, Wagh, & Wilensky, 2015; in materials science: Blikstein & Wilensky, 2009; in robotics: Levy & Mioduser, 2010). For example, in biology education, van Mil et al. (2013) suggested including measures for the development of molecular mechanistic reasoning to improve students' understanding of cell behavior as a complex system in which cellular processes emerge from molecular interactions. They claimed that a teacher can build on a student's intuitive reasoning about mechanisms. In a later paper, van Mil et al. (2016) demonstrated a way to do this by using a strategy based on students' interpretation of animations of (sub)cellular processes as models of molecular mechanisms. Conversely, Stieff (2011) found that learning high school chemistry through a complexity approach was no better than a normative approach for conceptual learning (although the complexity approach group improved in representational competence). The current study aimed to resolve this contradiction by identifying those situations and concepts in which existing normative curricula work well enough and those that might benefit from a complexity approach. It expands this body of literature by conducting a nuanced examination of learning with attention to particular science concepts and systemic components of reasoning.

Specifically, the present study examined how junior high school students learn such concepts as kinetic molecular theory (KMT), gas pressure, diffusion, temperature, and the gas laws. The definition of these concepts and the level of understanding were carried out in accordance with the knowledge required of students at this age.

3 | RESEARCH QUESTIONS

Our goal is to detect specific advantages and disadvantages of learning chemistry through a complexity perspective among junior high school students. By comparing the learning taking place in two kinds of settings: (1) a complexity approach using model exploration activities and laboratory experiments and (2) a normative approach, using lectures, textbook, and laboratory experiments, the following research questions are addressed:

- **(i)** *Conceptual learning by science concept*: How does students' conceptual learning regarding concepts related to a gaseous system—pressure, diffusion, temperature, density, KMT, and gas laws—compare between the two learning environments?
- **(ii)** *Conceptual learning by system components*: How does students' learning framed through a complex systems perspective—separation between micro- and macro-levels, transitions between levels, stochastic behaviors—compare between the two learning environments?

4 | METHODS

4.1 | Research approach

The secular study employed a mixed-methods approach combining quantitative analysis of questionnaires and qualitative analysis of interviews. The research was planned as a nonrandomized controlled quasi-experimental pretest–intervention–posttest design.

4.2 | Participants

Seventh-grade students (*N* = 104; 70 males) from three schools in the north of Israel participated in the study. Table 1 provides information about the participants and their schools. Five students (three boys and two girls), 10% of the experimental group, participated in interviews. These students were randomly selected by the teachers from a group of more articulate students. In terms of academic success, two were strong, two were medium, and one was weak.

The teachers were selected by their willingness to invest the necessary efforts to participate in the study and to learn the complexity approach to teaching, which included the computerized learning environment. All the teachers held an undergraduate degree in science education and had taught for over 10 years. The research was approved by the Ministry of Education. The student participants' parents all signed informed consent forms.

4.3 | Procedure

All chemistry classes (for both complexity and normative approaches) consisted of twelve 45-minute lessons, mostly double periods, as part of their seventh-grade science course. Learning through both complexity and normative approaches focused on the particulate nature of matter: KMT, gas pressure, temperature, and diffusion and the gas laws. These topics are typically studied in the early junior high school chemistry curriculum, forming the foundation of chemistry instruction. The experimental group used the complexity curriculum as a replacement for their usual curriculum on the topic. Before and after the activities, spaced 2–3 weeks apart, the students completed identical content knowledge questionnaires (pre–post test) within 30 minutes.

Five students from the experimental group were interviewed before and after the implementation and were recorded with a videocamera and voice recorder. The interview protocol was designed to expose the students' comprehension of scientific concepts and their knowledge of gas systems. The duration of each interview was about 15 minutes.

4.4 | Who understands gases? Curriculum

In a previous paper, Levy and Wilensky (2009a) have presented a conceptual framework underlying the design for learning about complex chemical systems (Figure 1) and demonstrated it through the first chapter in the Connected Chemistry curriculum (Levy, Novak, & Wilensky, 2006). The framework is based upon Johnstone's (1993) insightful analysis of chemistry knowledge represented as a triangle containing three knowledge components: the submicro (atoms, molecules, and their kinetics), the macro (tangible, edible, and visible phenomena), and representations

TABLE 1 Participants and schools

Schools/group	Experimental group	Comparison group
Rural mid-socioeconomic secular elementary school with 384 students	One class (*n* = 30)	
An Urban all-male mid-socioeconomic religious state-funded small school with 180 students	One class (*n* = 23)	One class (*n* = 19)
Urban, low-socioeconomic school with 450 students		One class (*n* = 30)

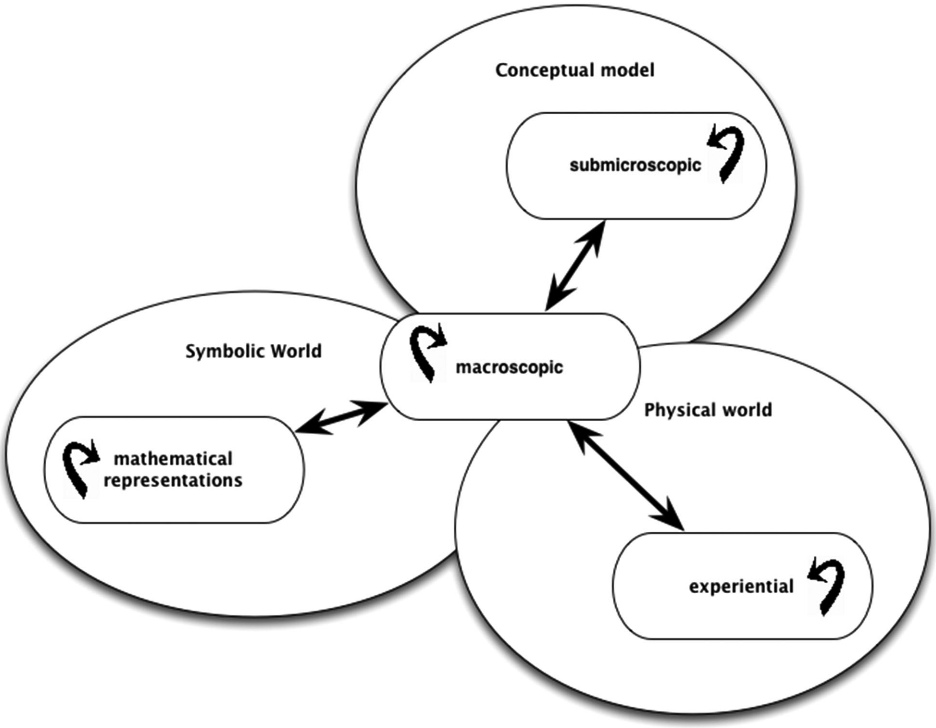

FIGURE 1 Conceptual framework for supporting learning about systems through agent-based models. Larger circles signify spheres of knowledge; smaller ones are forms of access to understanding the system; arrows signify the activities' learning goals—understanding each form of access individually and the connections between them

(symbols of chemical entities, chemical equations, and mathematical representations). The current framework depicts three knowledge spheres: conceptual learning of how molecular interactions result in a system's global behavior, symbolic-mathematical expressions of the system's behavior, and physical experiences of the explored phenomenon. Learning about the gas laws and KMT is typically conceptualized through four canonical forms of access: micro, macro, mathematical, and experiential. The framework is anchored at the experienced macroscopic level that is common to all three spheres of knowledge. The motivating hypothesis for the design is an educational setting that combines activities which foster an understanding of each form of access. The chemical system is explained with activities that promote multiple bidirectional transitions along the three bridges anchored at the experienced macroscopic level. This constitutes a rich and fertile environment that supports a deep and integrated understanding of the chemical system at hand.

Computer models, worksheets, class discussions, and laboratories were used to deliver and advance learning about basic chemistry concepts. The models were developed for the Connected Chemistry environment (Levy & Wilensky, 2009a). They were constructed using an ABM platform, NetLogo (Wilensky, 1999) that is used extensively in the domain of complex systems. In this way, a system can be displayed as a collection of identical entities that behave according to a few basic rules that lead to phenomena such as the pressure, diffusion, or temperature of a material. Furthermore, the models can be manipulated by the students so that changes at the micro-level can be shown to result in nonlinear changes at the macro-level.

In this study, a sequence of eight ABM models were used by the students. Other tools were developed for this study and included: (i) a workbook that guided the students through the presented topics, how to use the models, and any challenges or questions; (ii) class discussions to highlight the systemic characteristics of the phenomena studied; and (iii) laboratory experiments to anchor the computer models to daily life phenomena.

TABLE 2 "Who understands gases?": Learning environment and activities

	Activity	Number of lessons
1	Laboratory demonstrations and investigations to elicit students' questions, understanding and discussions regarding the unit's activities	1
2	KMT: Exploration of a simple KMT model, where the basic rules can be turned on and off; Summary and discussion	2
3	Gas laws: Demonstrations of phenomena related to pressure; Exploration of three models: vary the number of particles and observe pressure; vary volume and observe pressure; vary temperature and observe pressure; Definition of pressure, summary and discussion	5
4	Diffusion: Demonstration of phenomena related to diffusion; Exploration of a diffusion model; Summary and discussion	3
5	Summary and discussion of the whole unit	1
	Total	12

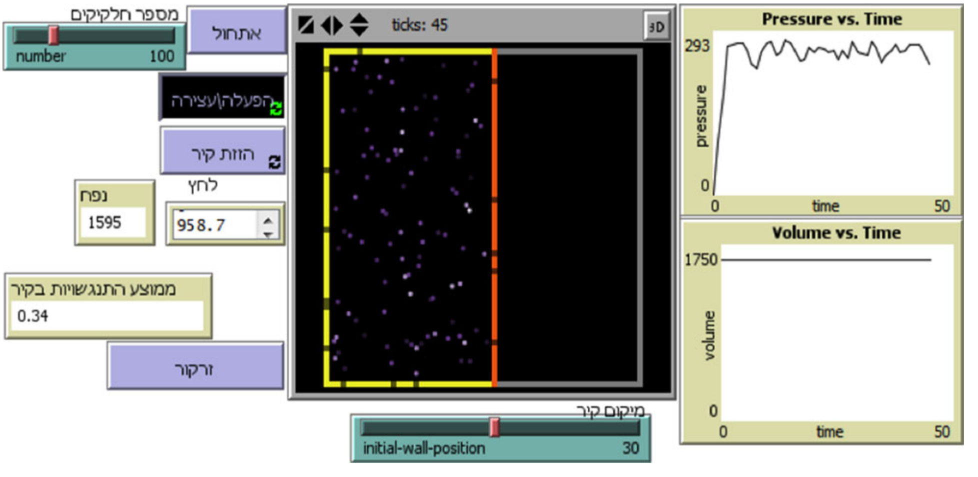

FIGURE 2 Volume-pressure model (Wilensky, 2005) screen shot. The box contains particles of varying speeds (in shades of violet). Pressure is computed from the rate at which the box walls are hit by particles. The two-dimensional volume of the box can be changed [Color figure can be viewed at wileyonlinelibrary.com]

The models include a submicroscopic representation of a gas in a container in the form of particles (points) located within a square as well as a global view of the system on the same scale on the screen. This access to the micro-level is enhanced by several supportive elements that help the students to notice individual particles within the simulation. In this study, the models were adapted for Israeli junior high school students by removing some of the mathematical representations, translating the names of the buttons and sliders into Hebrew, fine-tuning the activities in response to previous research (Levy & Wilensky, 2009b), enhancing and grounding the concepts with laboratory activities, and adding the culminating topic of diffusion. Table 2 describes the unit. Figure 2 demonstrates one of the computer models.

Details of the two interventions are provided below.

4.4.1 | Intervention 1: Complexity approach ("Who understands gases?" experimental curriculum)

The "Who understands gases?" learning environment (Samon & Levy, 2010) is made up of five activities and is 12 lessons long. It includes guided exploration of agent-based NetLogo (Wilensky, 1999) computer models of contained gas particles, laboratory experiments, and class discussions.

Students explored agent-based models of contained gas particles to examine and explain different day-to-day phenomena. A typical lesson began with either the teacher demonstrating a phenomenon or the students conducting a laboratory experiment. After this, the class discussed possible explanations.

The majority of the time was devoted to students' investigation of the scientific phenomena and studying the structure of matter through agent-based computer models guided by a workbook each student filled out. The students worked in pairs in front of a computer. The workbook guidance helped students focus their attention on single particles and their interactions and encouraged them to transition between the micro- and macro-levels. For example, an activity to explain the phenomenon of diffusion:

> *"Turn on your model: click on the start button. Describe the motion of a single particle. Click on the spotlight button. This button allows you to focus on a single particle and its immediate surrounding area so that you can track the movements of the particle and its interactions with other particles and with the wall of the tank. Focus on a single particle and describe the way it moves (does it move in circles, in straight lines or in S-shaped motions?)*
>
> *Did the particle move to the other side of the tank?*
>
> *If so, what caused the particle to get there? If it did not, why?*
>
> *Does particle movement stop after the perfume particles are uniformly distributed between air particles?*
>
> *Describe the behavior of particles in the process of diffusion of two gases."*

Thus, it can be seen that most of the questions put to the students were related to the micro-level. In this way, the students were able to focus on the emergence of the phenomenon from studying the dynamic interactions between gaseous particles. (For more examples, see Levy & Wilensky, 2009a). While working on their computers, the teacher conversed with individual students, answered their questions, and checked their answers. The lesson was concluded by the teacher writing the students' insights on the classroom board.

4.4.2 | Intervention 2: Normative approach (the regular curriculum)

The normative approach to chemistry education consisted of the teacher presenting the particulate model as a given theory, focusing on phases of matter, and exploring phenomena explained by the particulate model such as compression of gas in a syringe and perfume diffusion through air. In a typical lesson, the teacher introduced the existing theory and basic concepts, and wrote important facts and terms on the classroom board that the students then copied into their notebooks. The teacher usually demonstrated a phenomenon via a physical experiment or picture in a book. She would then ask the students to explain it on the basis of the particulate model, either orally or in their notebooks. Their answers would generate a discussion in which the teacher asked further questions and in turn, respond to any queries from the students. The lesson would conclude with a directive written on the classroom board or in the textbook for either class- or homework. Throughout the class, the teacher stood or sat at the front and would sometimes demonstrate a computerized particles model to illustrate the submicroscopic explanation (three relevant models exist, the display taking approximately 2–3 minutes each).

The textbook *A World of Matter* (Dayan, 2001) was used in the lessons, the most common textbook in Israeli schools at the time of this study. The following is an illustration of an example from this textbook showing the phenomenon of diffusion. The teacher would conduct an experiment with a bottle containing liquid ammonia. Red litmus paper would be attached to the bottle cork, so that when the bottle is closed, the litmus paper would turn blue after contact with the ammonia. Following this experiment, the teacher would ask the students the following questions:

What happened to the color of the paper?

How did ammonia reach the litmus paper?

In your opinion, can contact with the air outside the bottle with the litmus paper, change its color? Explain.

The air takes up space. So how could the ammonia vapor reach the litmus paper hanging on the cork?

Draw and describe (with different colored dots) the contents of the bottle in the space between the surface of the solution and the cork.

TABLE 3 Comparison of the two learning environments in the study, by frequency of questions pertaining to each system component

	Complexity approach	Normative approach
Macro-level	44 (40%)	91 (70%)
Micro-level	40 (36%)	23 (18%)
Micro–Macro transition	26 (24%)	16 (12%)
Total number of questions	110	130

The substance that caused the litmus paper to change color is the liquid ammonia at the bottom of the bottle. Prove this assertion.

Therefore, it can be observed that most of the questions dealt with macro-level phenomena. At the micro-level, the student is required to illustrate the particulate material; however, none of the questions addressed the dynamic phenomena.

Table 3 compares the number of questions addressed to the students in the two learning environments with respect to the systemic aspects of gases. This analysis was conducted on the videotaped data and the students' workbook. It can be seen that the normative environment included more questions in general and specifically, more macro-level questions; the complexity-approach environment had a higher proportion of micro-level and micro–macro transition questions.

4.5 | Data collection tools

The study examined conceptual learning of science concepts and of systems. To capture this information, two main data collection tools were used (Appendix A; Table 3): a content knowledge questionnaire and a protocol for a semi-structured interview.

The questionnaire was based on that used in previous research on learning gas laws, KMT (Levy & Wilensky, 2009b), and diffusion (Odom & Barrow, 1995) and was designed to correspond to the concepts taught in the lesson activities. Additional items were created in-house to obtain more information on students' reasoning about diffusion. The questionnaire included 24 multiple-choice questions, asking the students to describe, explain, and speculate about phenomena associated with the particulate structure of matter and the concepts of temperature, gas pressure, and diffusion using both macro-level and micro-level explanations. The questionnaire also included two open-ended questions that had the students draw a submicroscopic representation of perfume diffusing in the air, but those were not analyzed in the current study.

The interviews focused on three science concepts that required more sophisticated emergent reasoning: pressure, diffusion and temperature. In this paper, we reported participants' understanding of pressure and diffusion. The protocol for the interview included scenarios that the students were asked to describe and explain. For example, for diffusion, they were asked to explain what happens to perfume sprayed into an inflated plastic bag; for temperature, they were asked what happens to an inflated plastic bag when it is put into hot water. The questionnaire was designed to assess both the students' scientific knowledge and their systems reasoning. During the interviews, the students were provided with nontextual resources, including color pencils and coins to illustrate and demonstrate particle scattering and movement, to get a broader picture of the students' knowledge.

4.6 | Data analysis

The interviews were transcribed and used to examine different aspects of learning. This was to provide a more deep and enriched understanding of the findings from the analysis of the questionnaires.

The students' answers to the questions in the questionnaire were coded as correct or incorrect. Each item on the questionnaire was assigned a numerical score, where the overall score was an average of these scores, reflecting the equal status assigned to each item. As the questionnaire was aligned with the curricula, this score reflected their learning goals. A learning gain was computed to compensate for differences in prior knowledge: [(postscore) – (prescore)]/(prescore).

A concept-by-concept breakdown was then used to group the coded items and assign a specific concept score. In this way, every idea was tested using a number of phenomena. For example, to test the students' understanding of the diffusion of gases, this concept could be examined through expansion of perfume through the air, spreading a drop of ink in water, and looking at the micro-level of diffusion. Thus, comprehension of a phenomenon was examined by understanding various concepts such as gas compression, particle density, pressure, temperature, and volume of a gas. Finally, the items were coded according to the system components the students needed to understand to answer correctly. Thus, items that required an answer that relates to changes in the phenomenon level were coded as those relating to the macro-level of the system, items requiring explanation related to the behavior of matter particles were coded as those relating to the micro-level of the system, and items requiring an explanation of the observed phenomenon by the behavior of the particles were coded as involving micro–macro transitions (see Appendix B).

For analysis of the interviews, we chose the multiple-case narrative approach. This strategy can assist the researcher in dealing with a large number of narratives, to identify similar or distinct characteristics that have become apparent from comparing many cases (Shkedi, 2005).

The interviews were analyzed by breaking down the learned concepts into categories. The categories were determined in accordance with the scientific conceptual understanding required of middle school students and in accordance with the systems reasoning framework designed by Jacobson (2001). These included eight parameters used for comparison between novices and experts, regarding their understanding of complex systems: linkage between the micro- and macro-levels, local interactions, and equilibrium (Jacobson, 2001).

4.7 | Validity and reliability

The construct and criterion validity of the content knowledge questionnaires was reviewed by five science teachers, two of whom taught the "Who understands gases?" curriculum, and three who taught with the normative curriculum. All confirmed that the test items were appropriate for examining the concepts and ideas studied with the normative learning environment.

The two open-ended questions' responses were scored by the researchers and the participating teachers. Comparison of the independent scores and codes yielded 97% agreement on 184 items. Disagreements were resolved by discussion.

In analyzing the interviews, the two authors analyzed the transcripts independently and then compared their results. Initial agreement was 83%, which then increased to 92% following further conversations and several rounds of analysis.

5 | RESULTS

The findings are presented according to the research questions: conceptual learning by science concepts and learning by systems components.

5.1 | Conceptual learning by science concepts

Some students did not complete one of the questionnaires due to being absent from school, reducing the sample to $N = 92$.

Table 4 presents the total scores and learning gains from the content knowledge questionnaires for the complexity approach ($n = 47$) and normative approach groups ($n = 45$) via descriptive and inferential statistics.

TABLE 4 Pre- and posttest science concepts and systems scores (%), learning gains and statistical tests in comparing the two groups

				Pretest (%)		Posttest (%)		Learning gain (%)		Statistical tests
	Component	Number of items	Exp[a] M (SD)	Comparison M (SD)	Exp M (SD)	Comparison M (SD)	Exp M (SD)	Comparison M (SD)	Unpaired t (91)[b]	Cohen's *d*
Overall	Overall	26	45 (12)	43 (14)	75 (16)	54 (18)	74.9 (46)	31.2 (50.6)	4.33**	0.90
Science concepts	Pressure	5	60 (49)	54 (50)	86 (34)	72 (45)	69 (90)	46 (86)	1.24	0.3
	Diffusion	6	40 (55)	38 (48)	72 (45)	50 (50)	134 (138)	44 (87)	3.55**	0.78
	Temperature	4	40 (49)	30 (46)	72 (45)	47 (50)	46 (34)	24 (69)	1.19	0.78
	Density	8	48 (54)	44 (50)	74 (44)	57 (50)	70 (84)	27 (72)	2.53**	0.55
	KMT	9	38 (47)	41 (49)	76 (43)	47 (50)	100 (74)	42 (106)	3.32**	0.70
	Gas laws	11	56 (50)	49 (50)	82 (39)	65 (48)	64 (63)	48 (94)	0.97	0.20
Systems components	Micro	6	39 (49)	42 (49)	74 (44)	43 (50)	122 (110)	126 (85)	5.22*	1.12
	Macro	8	58 (55)	52 (50)	80 (34)	65 (48)	81 (112)	40 (97)	1.83	0.43
	Micro–Macro	11	48 (50)	42 (50)	76 (43)	58 (49)	85 (140)	56 (130)	0.93	0.21
	Probabilistic behavior	3	10.4 (81)	11.1 (86)	21.9 (83)	15.8 (103)	11.5 (12)	4.7 (11)	2.82**	0.59

[a]exp indicates the "experimental group."
[b]*marks significance of $p < .05$; **marks significance of $p < .01$.

Pretest scores were comparable for the two groups. Both groups improved significantly from pre- to posttests. However, the experimental group obtained a much higher posttest score. The experimental group's learning gain was almost three times that of the comparison group with a strong effect size.

The effect of the intervention on students' achievements was analyzed with an analysis of variance (ANOVA) test, that indicated that the instructional approach (complexity vs. normative) exerted a significant effect on differences in student achievement F (1, 87) = 19.418, p <.001, ${\eta^2}_{\sigma} = 0.182$. A main effect of interaction between group and school was also observed in the data set F (1, 87) = 5.423, p < .01, ${\eta^2}_{\sigma} = 0.59$: the learning gain in the complexity-approach group in school 1 was smaller than that of the normative-approach group in school 2. In school 1, the science teacher taught both complexity-approach and normative-approach groups. In school 2, the two groups were taught by different teachers. Thus, we interpret this result as a diffusion of effects, with the teacher in school 1 changing her teaching with the normative approach, from being influenced by the complexity approach she was teaching at the same time in the other class. School 1 also had a more homogeneous population than school 2. A multivariate analysis of variance (MANOVA) test showed that there was no teacher effect, and neither school type nor gender yielded a significant impact on the learning gain after the intervention.

Questionnaire items were grouped by concepts and their score was averaged (Tables 5 and 6). Three science concepts were mastered more effectively through a complex systems perspective: density, diffusion, and KMT. Regarding the other concepts—pressure, temperature, and the gas laws—the two curricula supported comparable learning gains.

The most substantial difference among the groups pertained to learning about diffusion, one of the more difficult concepts to understand (complexity approach,132% vs. normative approach, 47%). This difference is statistically significant with a medium-strong effect size. The complexity approach group also evinced a higher rate of improvement in regard to KMT (135% vs. 38%) and density (70% vs. 27%). The questionnaire findings regarding the concepts of pressure and gas laws indicated that the two groups both improved with comparable learning gains, so that the differences between them were insignificant.

5.2 | Conceptual learning from the qualitative observational data

Two concepts—pressure and diffusion—were analyzed in more detail to understand the quality of the experimental group's learning. Regarding the quantitative results, pressure was learned to a similar extent in both curricula, whereas diffusion was learned to a greater degree with a complexity approach. The data for this section are the pre- and posttest interviews with five students.

5.2.1 | Pressure

In the following examples, two findings are demonstrated: (1) initially the students held a continuous view of matter; however, after studying with complexity-based activities they took a particulate view, which distinguishes between the micro-level and the macro-level of the system for both properties and behaviors; and (2) a continuous view of matter, which provides a similar explanation of the concept, both at the micro- and macro-levels, supported the same predictions as the particulate view, thus explaining why there were no differences between the groups in the quantitative results.

An understanding of pressure that is based on a particulate view can be described as understanding how the random movement and collisions between particles and between particles and surfaces of a container are related to pressure. The formal scientific view at the micro-level that relates to the rate of perpendicular momentum transfer per unit area was not included as these concepts are not learned at the middle school level. Instead we focused on the speed and rate at which particles hit the walls of a container.

In the interviews, participants were asked about changes inside a closed plastic bag when air is pumped into it. Two main categories were used to analyze the interviews: (1) particulate or continuous view of matter and (2) pressure as a property of the whole (macro-level alone) or as emerging from collision interactions between the particles themselves and with the bag's sides (micro- and macro-levels).

TABLE 5 Sample items from the questionnaire and the interview protocol

Data source	Targeted concepts	Sample items
Questionnaire	KMT micro-level	When two gas particles collide: ○ Both their speed and direction will change. ○ Their direction can change but not their speed. ○ Their speed can change but not their direction. ○ Neither their speed not direction will change.
	Gas laws macro-level	Two basketballs have the same volume and are at the same temperature. The pressure in the first ball is larger than the pressure in the second ball. How is the number of air particles in each ball related to one another? ○ The second ball has more air particles ○ The second ball has less air particles ○ The two balls have the same number of particles ○ One cannot know which basketball has more particles
	KMT, diffusion Micro–macro bridge	Read the following section and answer the questions. A girl dabbed some perfume on her neck. Her mother, who was standing at the other side of the room called out: "What a good scent!" Draw how the perfume particles reached from the girl's neck to the mother's nose at the other side of the room. Use small circles to depict particles. Explain your drawing in detail. Describe in words how the perfume particles reached from one side of the room to the other. Explain how all the individual entities participate in the process.
Interview	KMT, pressure Micro–macro bridge	A blown up plastic bag is placed before the participant. Let's look at the blown up bag. What is inside? If we could wear magic glasses that would let us see this at a million times this size, what would we see inside the bag? Can you draw this? Explain your drawing with words. What are the objects that you've drawn? What do they do? What is between them? What is their size? Are they heavy? What is their shape? Is their shape constant?
	Gas laws, pressure macro-level	Two empty plastic bags are placed before the participant. I will now add air into one bag. What do you think will happen while the bag is being blown up? What is the difference between the empty bag and the blown-up bag?

In the pretest, four out of five participants demonstrated a continuous view of matter. Y drew the air as a single continuous blob within the bag and said, "The air looks like one unit that blows up." However, it is important to notice that his prediction regarding the air pressure in the bag is correct, although there is no distinction between micro- and macro-levels, "With a larger amount of air inside the bag, then there is more and more pressure, and in the end, it bursts, because it can't take it anymore." When N was given coins to describe the motion of air particles, it was evident from her facial expression and hand gestures that she was in a dilemma; she finally took a group of coins and pushed them all together into aggregate form, a single entity. G had a more advanced understanding that included air particles, but he described them with unrealistic scales, "That's when they are close together and don't have room to move, like in solitary confinement."

Four of the five students observed shifted from a view of pressure as a continuous structure to one integrated with a KMT-based particulate view. All of them exhibited increased awareness of the micro-level of the system and of the importance of interactions at the micro-level for understanding pressure, distinguishing between the two levels and relating them. We have seen Y above describing the air in a balloon as a single entity. In the posttest interview, he shifts to a detailed description of the particles, collisions, and walls of the container, that he connects with the macro-level

TABLE 6 Conceptual learning by science concept, tests of between-subjects effects

Source		Type III Sum of squares	Mean square	F^a	Significance	Partial eta squared
Concept	Pressure	0.322	0.322	0.386	0.536	0.005
	Diffusion	12.802	12.802	9.363	0.003	0.115
	Temperature	0.405	0.405	1.968	0.165	0.027
	Density	3.777	3.777	6.492	0.013	0.083
	KMT	17.468	17.468	10.986	0.001	0.132
	Gas laws	0.274	0.274	0.552	0.460	0.008

[a]df in all items is equal 1.

property of pressure, “There will be pressure because there will be too many particles and that will cause pressure, lots of collisions, and then these collisions will also reach the walls [of the container] and will start blowing up [the bag].” In this way, Y was able to explain a macrophenomenon from a micro-level perspective. Similarly, R explained, “Pressure is force per unit area. Particles collide with the balloon walls, causing pressure.” G is ambiguous in his approach. On the one hand, he was also able to shift to a particle view and with the use of the coins, describes the movement of particles in the bag. On the other hand, when he was asked to show what happens when a balloon explodes, he moved the coins toward the walls of the balloon, holding the coins close together as a continuous single continuous entity. His words and actions contradict, as he moved them together toward the sides while saying that “the particles exert a strong force on the walls, so that the balloon cannot be pushed anymore and explodes.” G’s continuous approach at the walls served him better to explain the macro-level concept of pressure as force per unit area and to coordinate it with micro-level collisions of particles with the balloon’s walls.

From the above example responses, it was observed that the pre- and posttest ways of thinking about matter were distinct; moving from a continuous view to a particulate view. The concept of pressure shifted from that of a bulk property to an emergent property of the particles’ collisions. Nevertheless, it is important to notice that changes in pressure were predicted correctly with both views of matter. Since the quantitative results also showed similar learning gains regarding pressure with both curricula, it can be seen that with or without a micro-level particulate or complexity view, students could correctly predict how pressure changes.

5.2.2 | Diffusion

In the preceding section, it was observed that pressure was explained by the students differently in the pre- and posttests, but the distinct explanations supported similar predictions. In the case of diffusion, this was not the case. In fact, predicting diffusion with a continuous model of matter, which does not provide a distinction between micro- and macro-levels, led the students to incorrect predictions. Diffusion is a particularly challenging phenomenon to understand, as the micro-level behaviors (random motion in all directions) seems to conflict with macro-level phenomena (an overall move of matter from higher to lower concentrations).

In the interviews, the participants were asked to explain what happens to perfume sprayed into an inflated plastic bag. Three main categories were used to analyze the interviews: (1) a particulate or continuous view of matter, (2) homogeneity versus heterogeneity in the distribution of two kinds of matter (air, perfume), and (3) random motion of the particles versus directional motion of the bulk of matter.

In the pretest interview, all five students predicted that the perfume would sink to the bottom of the bag, describing a directional motion of the mass of perfume. Students’ lack of experience with the concept of scent as molecules in the gaseous state that reach and interact with their nose could be the source of their view that perfume stays in the liquid phase. R described the perfume in the bag, “It [the bag] will have inside both air and perfume.” She proceeded to draw the perfume as an orange blob at the bottom of the bag (Figure 3). She explained, “It [the perfume] is heavier than the air and sinks to the bottom.” When the interviewer asked her about the air that was in the bag previously, she says, “It pushes the air.” Using two coins, one to represent the bulk of perfume and one to represent the bulk of air, she

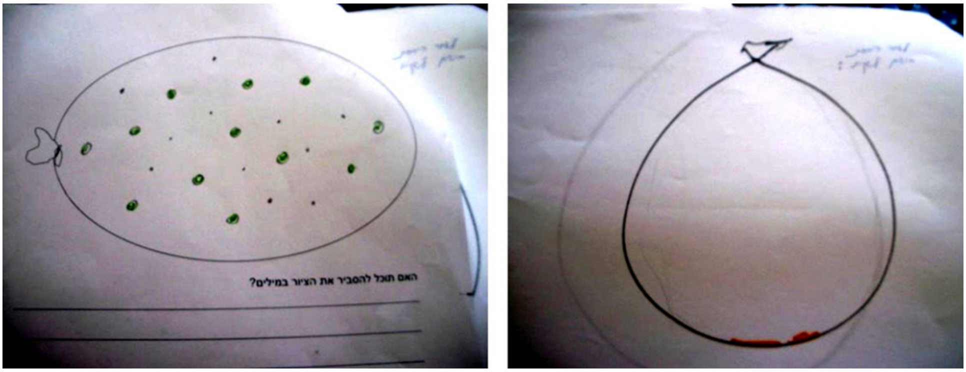

FIGURE 3 R's drawings of perfume and air inside a balloon before (right, perfume has fallen to the bottom of the balloon) and after (left, both air and perfume particles are represented homogeneously in the space of the balloon) learning with the "Who's afraid of gases" curriculum [Color figure can be viewed at wileyonlinelibrary.com]

demonstrated how the perfume blob pushes the air blob aside and said, "because it [the perfume] is heavier than the air, it pushes it aside and falls to the bottom." Thus, the two kinds of gas were viewed through a continuous perspective of matter as nonmingling masses, one heavier than the other that cannot take up the same space. They are viewed as macro-level entities with directional motion.

Distinct from directional motion of a mass, their explanations after the intervention, which shift to describing particles' micro-level motion that is random and scattered in all directions. After the intervention, the students' perception changed. Their drawings showed a homogeneous distribution of particles in space with perfume particles between the air particles (Figure 3). They all drew a uniform distribution of particles in each bag, with circles that represented the perfume particles moving between circles that represented the particles of air.

As R noted, "Perfume particles will be mixed together with the air particles." Three students related to both micro- and macro-levels in their explanations and mentioned that the uniform distribution of perfume at the end (description of the macro-level) was due to random collisions between the particles (at the micro-level). For example, N said, "The particles will all be scattered because of collisions"; and B said, "The mixing [of the air and perfume] results from their motion and collisions between the particles." One student indicated that the two materials would be uniformly distributed because of the vacuum between the particles: C explained. "You can spray perfume into a bag full of air because space exists between [the particles] and it's called a vacuum, the perfume particles enter the vacuum."

As the answers evince, the students made the shift to a micro-level particulate view of gas, improving their understanding of random particle motion and interactions and abandoning the idea that particles have a will of their own, while basing their explanations on physical phenomena of motion and interactions.

Different from the concept of pressure, the continuous view of matter seen in the pretest interview did not support a correct prediction of diffusion at the macro-level. In the pretest, participants predicted the perfume would fall to the bottom as it is heaver, and in the posttest they predicted it would spread.

5.3 | Conceptual learning by systems components

The "Who understands gases?" curriculum was designed with a complexity perspective, encouraging students to investigate the micro-level and emphasizing how the macroeffects result from interactions between particles at the submicroscopic level. To examine whether such a complexity approach is effective in improving the perception of chemistry-related phenomena as systemic, an analysis was performed by system concepts. The questionnaire items were divided into those relating to the micro-level, those addressing the macro-level, and those requiring transition between the two levels. The descriptive statistics are presented in Table 4.

The MANOVA results indicated that the complexity approach improved understanding of chemical systems ($F_{(3,81)} = 9.046$, $p < 0.001$, $\eta^2_\sigma = 0.251$). The general significance stemmed from understanding the micro-level ($F_{(1,83)} = 25.471$, $p < 0.001$, $\eta^2_\sigma = 0.235$). No significant differences were found in learning gains for systems thinking at the macro-level ($F_{(1,83)} = 3.20$, $p = 0.077$, $\eta^2_\sigma = 0.037$) or regarding transitions between the micro- and macro-levels ($F_{(1,83)} = 0.493$, $p = 0.485$, $\eta^2_\sigma = 0.006$).

Learning gains were higher for the experimental group on all dimensions. The comparison group advanced in some dimensions as well: the macro-level and micro/macro transitions. The experimental program was significantly higher with a strong effect size only for understanding the micro-level of the gas particles. Both groups advanced in their understanding of micro/macro transitions, the experimental group with a much higher learning gain (85% vs. 56% for the comparison group); however, the differences were not significant.

Thus, if we were to relate the systems' components comparison to that of the science concepts learning, it would seem that a deeper understanding of the micro-level is related to a better understanding for those scientific concepts that showed specific advantages of the complexity approach.

6 | DISCUSSION

In this study, the particular levers by which a complexity approach empowers science learning were investigated by exploring students' learning of an array of concepts that are related to a system of gas particles. We compared the learning of concepts through a complexity approach with their learning through a normative approach.

6.1 | Learning science via a complex systems view

A distinct and strong advantage was found for learning the topic of gases through a complexity perspective, that is, one that emphasizes micro-to-macro reasoning about complex systems. Notably, the data collection tools used to arrive at this finding were those that were deemed appropriate for testing the normative curriculum by five experienced teachers. Thus, with regard to standard science education, we have seen learning gains with a complexity approach that almost tripled those obtained with a normal curriculum. This is an important and central finding.

This study adds to a growing body of research showing that a complexity perspective supports learning at various ages for different topics (Levy & Wilensky, 2009b, 2010; Blikstein & Wilensky, 2009; Brady et al., 2015; Holbert & Wilensky, 2014; Sengupta & Wilensky, 2009; Stieff & Wilensky, 2003; Wilensky, 2003; Wilensky & Reisman, 2006; Wilkerson-Jerde et al., 2015).

When considering chemistry education in schools, a previous study by Stieff (2011) showed no conceptual learning differences from comparing complexity and normative approaches. In the current study, we used a more fine-tuned lens, observing learning of both the diverse scientific concepts and the system dimensions. Like Stieff, we find that some of the concepts were similarly learned in both groups. However, regarding other concepts, we have observed a difference between the two approaches to learning. This suggests that different concepts should be examined separately, as they benefit to different extents from a complexity approach.

This study's findings point to the particular advantage of learning through a complexity perspective: understanding the particulate micro-level rules and their stochastic behaviors. It would seem that observing and reasoning about specific individuals in a system supports a stronger conceptual learning of phenomena at hand. One would expect that there would be a large difference between the two groups in making micro/macro transitions as well. However, this did not bear out in the results. While both groups advanced in their understanding of micro/macro transitions, with a large difference in means in favor of the experimental group, this difference is not significant. One possible explanation is that the sample was not large enough or the questionnaire was not sensitive enough. Another possible explanation is that normative chemistry teaching carries with it the learning of certain systems components, such as relating molecular behaviors to the bulk. We are now working on a study that entertains this possibility and looks into it from a number of perspectives.

Students' experience with dynamic models of micro-level particles that interact and collectively form the macro-level phenomena, both shown on the same scale in the computer model, strongly supports the students' ability to relate between the micro- and macro-levels. Moreover, the curriculum design includes experiences with individual particles, such as following them around on the screen. Such an increased attention to the detailed behaviors of the micro-level entities may seem like a waste of time, being idiosyncratic to local shifting contexts, averaging out over large ensembles of particles. To explain why such understanding of the micro-level particles supports learning of the macro-level concepts and patterns, we turn to Wilensky and Reisman's (2006) notion of embodying the individual in the system. In their research, they observed high school students exploring and explaining emergent behaviors while building models of ecosystems and population dynamics. Having an intuitive grasp of the individuals through their own experiences in the world, such as eating and walking, enabled the construction of these models by "thinking like a wolf, a sheep or a firefly." Obtaining a clear understanding of the distinct individuals and their local interactions supports a deeper connection between them as they *causally* emerged into the observed global patterns.

Many studies described in the literature review show students' difficulties in understanding phenomena related to the structure of matter, which are often associated with understanding the systemic nature of the studied phenomena, such as confusion between levels and not noticing interactions. It would seem that learning through a complexity approach alleviates at least some of these difficulties.

Learning via a complexity approach using the ABM models provides the following benefits: (1) *It simplifies the system:* The student has to identify the agents that comprise the system and the rules that govern them. This allows the student to focus on one individual agent and its behavior and local interactions according to a set of simple rules. With the use of computer models the student is able to learn that the same basic rules adopted at the individual-level can directly cause macro phenomena. (2) *It relieves cognitive load*: Computerized visual simulations show simultaneously the behavior of many agents, removing the need to deal with concurrent interactions. The reduced cognitive load releases cognitive resources to understand the overall features and details of the system (Levy & Wilensky, 2008). Presenting a sequence of interactions in the model saves the students having to expend effort in thinking about the dynamics of the system and allows them to perform cognitive processing relating to the rules that underlie the interactions. Direct causal reasoning is considered a natural way toward understanding the interactions of the different agents within the system. (3) *It provides universal schemes for interpreting a wide array of phenomena*: Investigation of the model allows students to either focus on one agent, on small groups, or on the whole system, enabling them to move between these three levels of description and study the laws that are characteristic to each level. Students can create an "intermediate level" by changing the number of items in the simulation from a large number to a smaller number or vice versa (Levy & Wilensky, 2008). Finally, (4) *It reinforces learning*: Students are able to investigate the structure and behavior of items at the micro-level and practice a variety of scenarios with different conditions and processes. This assimilates and reinforces learning of abstract schema and thus strengthens understanding with increased exposure (Bayesian learning; Domingo & Pazzani, 1996). This is especially beneficial when learning difficult concepts that require a good understanding of their systemic behavior.

6.2 | Micro–macro compatibility

Based on the findings of this study showing the benefits of a complexity approach compared to the normative approach in teaching some chemistry concepts but not others, we suggest the new construct of "micro–macro compatibility." This describes the degree of perceptual similarity between a system's behaviors described at both the micro- and macro-levels so that a specific concept can be understood. We describe this construct and use it to offer an explanation for how, for the same system, some concepts were learned much better with a complexity perspective (diffusion, density, and KMT); whereas others benefited comparably with a normative approach (pressure, temperature, and gas laws). A complexity approach benefits learning more for concepts that have less micro–macro compatibility. When behaviors at the two levels are less similar, focusing on individual entities and carefully separating their behaviors from those of the whole system is necessary for constructing a mechanistic explanation. When behaviors at the two levels are perceptually similar, the macro-level behavior can be extended to the micro-level and vice versa, in a way that does not necessitate understanding emergent processes.

As we will show, pressure and temperature show greater compatibility, whereas diffusion and density show less compatibility.

KMT rules operate at the particulate micro-level alone, and thus require a complex systems perspective. The gas laws operate at the macro-level and can be predicted without referring to the particulate level.

Pressure at the macro-level is viewed as the force (per unit area) exerted on any surface. When particles collide with the walls of a container they apply a push, or a force. The macro-level force applied by a group of particles and the micro-level collisions can both be seen as pushing against the container walls. Thus, we see a similarity between the push of a large mass of air inside a container with the small pushes exerted by many particles. In this case, the micro- and macro-level behaviors are compatible with each other. In the interviews, most of the students shifted from a concept of matter as a spreading continuous mass exerting force on the walls of a container to a scientific and mechanistic conceptual understanding. This shift is easier because of the similarity between behaviors at the two levels. Therefore, students in both groups—those learning with a complexity approach, and those studying with a normative approach—improved their understanding of pressure to a similar extent.

Rising temperature is associated with greater agitation as both the micro-level increase in molecular speeds and greater macro-level activity or motion. Even with a continuous view of matter, higher temperatures are associated with greater movement of matter, sometimes seen as bubbles in a liquid or as faster motion of the mass of matter (Osborne & Cosgrove, 1983). At the particulate level, the molecules' speeds increase with the rise of temperature as they move about faster. This compatibility between the micro- and macro-levels makes the transition between them easier. It is important to notice that this notion of temperature as particles' speed of motion needs to be elaborated in further learning as the concepts of thermal energy, heat, and temperature needs to be distinguished. This is an example of a more general problem that might rise, regarding the illusion of understanding that may form for micro–macro compatible concepts. As we have shown in the interviews, G reached a scientific conclusion regarding pressure, whereas his micro-level explanation was incorrect. Having a sense of coherence between micro- and macro-level behaviors without actually going through with the causal reasoning could be problematic in refining these concepts to scientific ones and needs to be addressed through further design, activities, and discussions.

For these two concepts—pressure and temperature—the two levels are more easily coordinated even without resorting to disentangling emergent processes.

Macro-level diffusion shows directional changes in the amount of diffusing matter over space, as a higher concentration of a substance in one place gradually spreads out to a homogeneous distribution. However, at the micro-level molecules are moving randomly in all directions, colliding and changing their heading. The behaviors at the micro- and macro-level are distinct. This concept demonstrates less micro–macro compatibility. In the interviews, we have seen an important change from macro-level entities with directional motion (macro-level) to the randomizing effect of collisions on the particles' motion (micro-level) and their gradual spread. The behaviors at the two levels of description are distinct, making it more difficult to relate. Coordinating between the two levels is not straightforward and requires emergent reasoning bolstered by appropriate supports. As a result, we can see a large difference between students' learning about diffusion in the two approaches.

Density at the macro-level is the ratio between a substance's mass and its volume. Without a particulate model, one can think of greater density as having "heavier" matter for a given volume. A micro-level description of density involves both the mass of the particles and the empty spaces between them, an uneven distribution of mass throughout space. This is a very distinct form of thinking, showing little micro–macro compatibility. Resolving these two ways of thinking about density is quite sophisticated and needs emergent structures to connect these distinct forms of reasoning.

Diffusion and density have less micro–macro compatibility, and their learning benefits largely from a complexity approach.

One might raise the question of whether the term micro–macro compatibility refers to particular phenomena, rather than concepts. Our study helps disentangle this question empirically. We have looked at single concepts across several phenomena, and we have looked at several concepts for single phenomenon. For example, students' understanding of pressure (concept) was explored both in pumping up a basketball (Phenomenon 1) and in pressing down on a syringe (Phenomenon 2). Conversely, we studied students' understanding of pressure, temperature, diffusion, and density (four concepts) relating to a gas moving between two rooms, a single phenomenon. In both setups, students were systematic in reasoning across concepts in different phenomena. Moreover, for a single phenomenon, they showed understanding for some concepts but not others.

This brings us the question of how an increase in a phenomenon's complication in terms of the conceptual structure is related to the use of micro–macro compatibility that addresses single concepts. In the study, we examined the understanding of relatively simple phenomena who's understanding usually involves understanding two or three scientific concepts. To understand more complex phenomena using the micro–macro compatibility construct, one needs to elaborate the concepts needed for their understanding. For example, to understand the phenomenon of a rising hot air balloon, the concepts of heat, temperature, pressure, diffusion, density of matter, mass, and weight need to be considered. The increase in heat imparts kinetic energy to the particles of the gas in the balloon, the particles move faster (as the temperature rises), colliding more frequently, and increasing the rate of diffusion. Some exit through the lower opening, where there is no wall. The same number of particles now occupies a larger space and has a lower density. The lower density of air inside the balloon results in its floating up in the air outside, which is denser. This explanation could become more detailed if we consider the different forces operating on the balloon's walls on the inside and on the outside. One could predict that students' initial understanding of phenomena that involves several concepts would be based on the more compatible temperature and pressure and less on concepts of particle density and diffusion. If one wanted to design for learning of the topic, learning of the latter two would need to be supported more than the first concepts.

Concepts whose micro- and macro-levels are more highly compatible can be understood through direct causal reasoning (A leads to B, Chi, Roscoe, Slotta, Roy, & Chase, 2012), with direct schematic thinking being a more intuitive operation (Spelke, Phillips, & Woodward, 1995). Students also assume that the micro-level pattern corresponds to the macropattern level (Chi, 2014). The presumption of a direct link between an entity's surface and deep properties constitutes a powerful cognitive heuristic thinking tool (Talanquer, 2009), pervasive even amongt college chemistry students (Talanquer, 2008). However, this kind of thinking is inappropriate for understanding concepts in which the micro-level behaviors differ from behavior at the macro-level.

Chi (2005) and Chi et al. (2012) distinguished between two kinds of systems: emergent and sequential systems. They characterize sequential systems, such as the circulatory system, as those where some components are more dominant in establishing causality, and the collective behavior is a linear sum of its components' behavior. One of the features they use to distinguish between the two types of systems is a *correspondence* or *a disjoint* between the processes at the micro- and the macro-levels of the system. They claim that in sequential systems, there is a relationship of correspondence, where the behavior of the individual entities in the system is correlated with the overall pattern. In contrast, emergent systems display a relationship of disjoint, or independence of the macro-level behaviors with respect to those at the micro-level.

It may seem that the micro–macro compatibility construct is the same as correspondence in Chi's (2005) work. However, it is important to distinguish between characterizing the system itself and characterizing the mental processes needed for understanding a specific concept. We have observed learning of different concepts related to the same system and found different levels of students' learning in the normative approach group. The basis for compatibility is not related to whether or not the system is emergent—we are discussing a single emergent nonlinear system—but to the particular behaviors each concept requires us to focus upon and encode. While pressure encourages us to attend to particles hitting a surface, temperature invites us to notice the particles' speed of motion. When we focus on temperature, we might not pay attention to the particles hitting the walls of the container, but to some distribution of speeds of the particles moving in the main part of the container. Thus, micro–macro compatibility relates to the understanding of a particular concept or construct, and not to the system itself.

Given the greater learning of the micro-level with the complexity curriculum, together with the micro–macro compatibility construct, it would seem that a complexity approach shifts learning by offering a two-level view of phenomena that supports disentangling the levels when they are dissimilar so they can be carefully connected later on.

6.3 | Limitations of the study

This study has a number of limitations. First, this was a short-term study, testing for a longer time interval may show any possible further benefits of long-term learning. Second, our proposed concept of "micro–macro compatibility" addresses chemistry topics taught at the beginning of junior high school students and further research is required to see if is also relevant for studying more complicated phenomena that require a higher level of understanding, testing for the helpfulness of micro–macro compatible concepts as a resource for making sense, and limitations posed by the incompatible concepts. Additionally, this was not a randomized study, and so there is a potential that there are other relevant differences between the two approaches that we have not addressed. One such factor is that participation in this study required considerable investment from teachers. Accordingly, the study population was determined by the teachers who expressed their willingness to participate. The enthusiasm of the teachers to teach using the complexity approach is likely a factor in the students' ability to learn, while unwilling teachers may produce a less positive outcome. The effect of correct answers based on the probability of guessing the correct answer has not been included in the analysis. Finally, although the students were randomly selected for interviews, they might nonetheless present idiosyncratic features that make them unrepresentative. Generalization of the findings to other groups must thus be undertaken with caution. The quantitative findings are based on analysis of multiple-choice questions. It may be that the intervention helped in ways that are not reflected in the quantitative data. Future research should include an analysis and comparison of students' interviews—those who learn with a complexity and a normative approach, to explore students learning and understanding the particular advantages of the complexity-based curriculum.

6.4 | Conclusions

A complex-system perspective offers important principles for understanding many scientific phenomena (Goldstone & Wilensky, 2008). Grasping these principles is becoming an essential part of every scientist's knowledge and skills. However, this perspective has yet to be fully adopted within the K–12 curriculum. The introduction of computerized tools into the classroom requires an effort on the teachers' part. To effect change, it is necessary to provide evidence regarding the effectiveness of these new forms of teaching.

Our assessments of understanding were based on existing normative perceptions of the domain. If we were to design and use tests that addressed ways of thinking that are more compatible with complex systems, such as discovering micro-level rules, asking more questions about how the macrostates evolve from microinteractions and asking what–if questions about the system's evolution over time, one may project that even greater learning gains would be evidenced.

The study presents four main highlights:

1. Learning with a complexity approach strongly benefits the learning of science in middle schools.
2. The way this happens is by helping students better notice micro-level objects and their interactions and the probabilistic nature of their behaviors.
3. With respect to the normative curriculum, some concepts (particulate-level KMT rules and the concepts of density and diffusion) benefit from learning with a complexity approach more than others (pressure, temperature, and the gas laws). These latter concepts are also less similar in their micro- and macro-level behaviors.
4. "Micro–macro compatibility" is offered as a construct to describe the degree of perceptual similarity between micro- and macro-level behaviors and detect phenomena that would be better taught using a complexity approach. An important implication of this study is the utility of detecting concepts in the science curriculum with less micro–macro compatibility. These concepts would turn into likely candidates for new learning designs that include emergent processes and corresponding computer models and pedagogical supports. This would promote a stronger understanding of science, particularly when causal reasoning between micro- and macro-levels would benefit from overcoming nonemergent views of systemic phenomena. For example, one could predict that learning about chemical equilibrium would benefit from a complexity approach. At the macro-level, chemical equilibrium is a stable state,

with no change. However, at the micro-level, chemical reactions are taking place continuously. This system shows less micro–macro compatibility, and learning it requires a focus not only on the micro- and macro-levels but also on how the stable macro-level behaviors results from continuous changes at the micro-level.

It is hoped that the findings of this study illustrate the advantages of teaching via a complexity approach, as well as offering a means of identifying which school science topics could become much more easily learnable with its use.

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APPENDIX A: WHO UNDERSTANDS GASES?

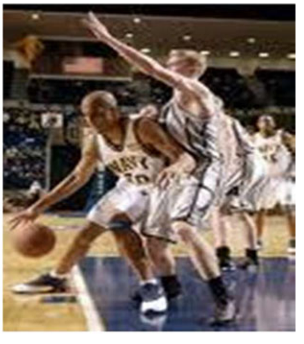
PRE- AND POSTTEST CONTENT KNOWLEDGE QUESTIONNAIRE

* correct answers

Question 1

A group of players want to play basketball, so they bring out a basketball that looks fine. But, when they try to bounce the ball, it does not bounce well (see Picture 1, below left). After pumping the ball with air, it bounces very well (see Picture 2, below right).

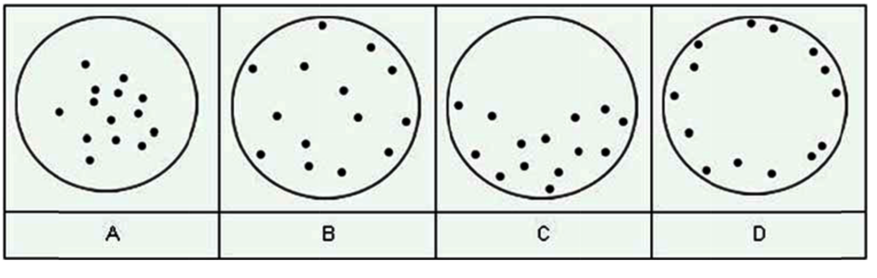
Picture 1



Picture 2

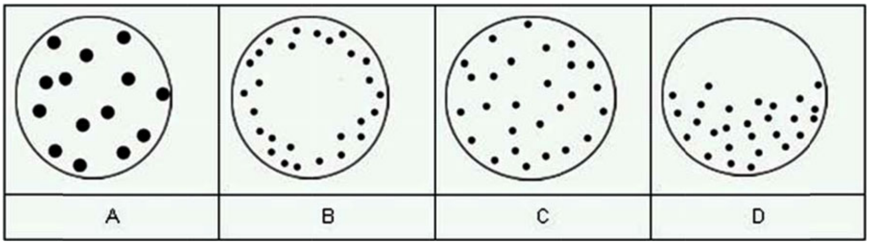
Let us say that we could take a snapshot of the air particles inside the basketball, as the pictures above show. In the drawings on the next page we will represent these particles. The particles are represented as much larger than they are in reality. We assume that the size of the basketball does not change.

Which picture best shows the way air particles could be distributed in the basketball BEFORE it gets pumped up? (*B)



Question 2

Which picture best shows the way air particles could be distributed in the basketball AFTER it gets pumped up? (*C)



Question 3
When two gas particles collide (A)

(A) * Both their speed and direction will change.

(B) Their direction can change but not their speed.

(C) Their speed can change but not their direction.

(D) Neither their speed not direction will change.

Question 4
If you cool gas in a container, what will happen to its pressure? (A)

(A) *The pressure will go down.

(B) The pressure will stay the same.

(C) The pressure will go up.

(D) You cannot know.

Question 5
Let's say you increased the number of particles in a container with a constant volume. What will adding the particles do to the pressure? (C)

(A) The pressure will go down.

(B) The pressure will stay the same.

(C) * The pressure will go up.

(D) You cannot know.

Questions 6–7 apply to the following information. Read it and answer the questions.
A basketball is pumped with air. Let's assume that the size of the ball doesn't change and that the temperature is constant.
Question 6
What happened to the rate at which particles collided with the sides of the ball after inflating it? (A)

(A) * Increased

(B) Decreased

(C) Remained the same

Question 7
What happened to the air particles after the ball was inflated? (B)

(A) The air particles hit the ball at a greater rate and collided with each other at a smaller rate.

(B) * The air particles hit the ball at a greater rate and collided with each other at a greater rate.

(C) The air particles hit the ball at a smaller rate and collided with each other at a smaller rate.

(D) The air particles hit the ball at a smaller rate and collided with each other at a greater rate.

Question 9

Two balls have the same volume and are at the same temperature. The pressure in the first ball is greater than the pressure in the second ball. How are the number of air particles in each ball related to one another? (A)

(A) * The second ball has a greater number of air particles than the first ball.

(B) The second ball has Smaller number of air particles than the first ball.

(C) The two balls have the same number of air particles.

(D) You never know which ball has a greater number of air particles.

Question 10

Which of the following rules does NOT describe the behavior of air particles, according to the Kinetic Molecular Theory (KMT)? (D)

(A) Gas particles move in straight lines, until they collide with something.

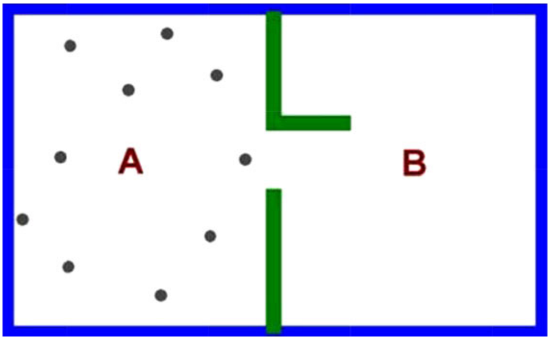
(B) When gas particles hit the wall, they bounce away, with no change in speed.

(C) Gas particles are much smaller than the distance between them.

(D) * When two gas particles collide, they react and form a new substance.

Questions 11–14 apply to the following diagram and information, read it and answer the questions.

Imagine a box with a wall inside it as in the following picture. One side of the box [A] contains a gas. A window is then opened in the wall that separates the two parts of the box.



Question 11

Which statement best describes the gas particles' motion? (A)

(A) * The gas particles in A are moving randomly about. If they happen to reach the window they go through it to B. Particles from B can go back to A.

(B) The gas particles in A are moving randomly about. If they happen to reach the window they go through it to B. Particles from B will not go back to A.

(C) The gas particles in A are moving randomly about. When the window opens, the particles head for the window to fill the empty side of the box, B. Particles from B can go back to A.

(D) The gas particles in A are moving randomly about. When the window opens, the particles head for the window to fill the empty side of the box, B. Particles from B will not go back to A.

Question 12

How would you describe the motion of a single particle? (B)

(A) A particle tends to move to the right more than it tends to move to the left.

(B) * A particle moves in a random direction, depending on the objects it collides with.

(C) The fastest particles rush to the right into the empty space that opened up.

(D) When an empty space opens, a vacuum is created that draws the particles.

Question 13

When a particle hits the wall of a container: (A)

(A) * The particle changes direction, but its speed remains the same.

(B) The particle changes direction and speed.

(C) The particle changes speed but not direction.

(D) The particle doesn't change its speed or direction.

Question 14

When two particles collide: (C)

(A) The particles change direction, but not speed

(B) The particles change speed, but not direction

(C) * The particles change direction and speed

(D) Nothing changes

Question 15

How does the mass of a particle impact its speed when pressure and temperature are the same? (B)

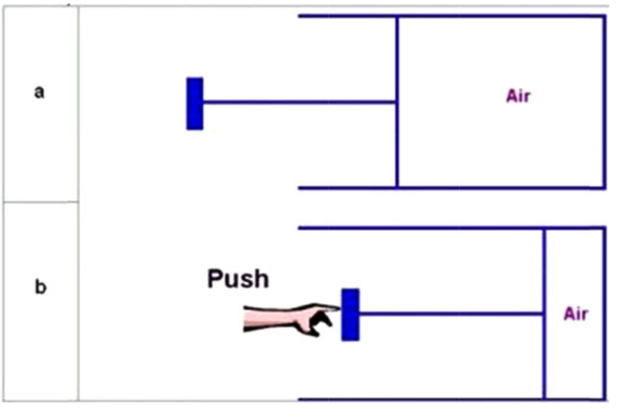
(A) When the mass is larger, the particle is faster.

(B) * When the mass is smaller, the particle is faster.

(C) There is no connection between the mass and speed of a particle.

(D) None of the above.

The following diagram shows a piston in a sealed cylinder. In (b) the piston has been pushed in. No air entered or left the cylinder. Let us assume that no energy was added or removed and that the temperature is constant. Questions 16–20 refer to the following diagram.



Question 16

The volume is (B)

(A) The same

(B) * Larger in (a)

(C) Larger in (b)

Question 17
The density of the air is (C)

(A) The same

(B) Larger in (a)

(C) * Larger in (b)

Question 18
The space between the particles is (B)

(A) The same

(B) *Larger in (a)

(C) Larger in (b)

Question 19
The average speed is (A)

(A) * The same

(B) Larger in (a)

(C) Larger in (b)

Question 20
Frequency of particle collisions is (C)

(A) The same

(B) Larger in (a)

(C) * Larger in (b)

Read the following section and answer the questions.
A girl sprayed some perfume on her neck. Her mother, who was standing at the other side of the room, called out: “What a good scent”!

Question 21
Describe in a drawing how the perfume particles reached from the girl’s neck to the mother’s nose on the other side of the room.

Use small circles to depict particles.

Question 22
Explain your drawing in detail. Describe in words how the perfume particles reached from one side of the room to the other. Explain how all the individual entities participate in the process.

____

____

Question 23
A drop of ink was put into a container with water. After several hours, the color of the water in the tank turned bright blue. At this point: (B)

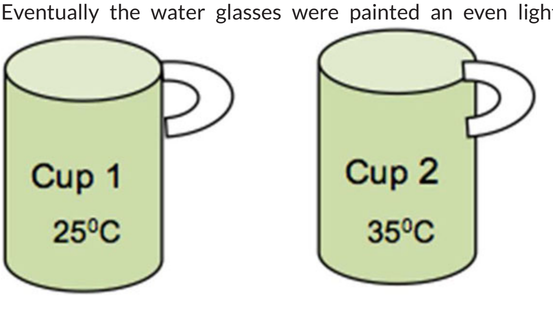
(A) ink particles stop moving.

(B) * ink particles continued to move randomly in all directions.

(C) ink particles began to sink to the bottom tank.

(D) ink is fluid. If it were solid, the particles were stop moving.

Question 24.1
You are presented with two large glass cups, which are identical in shape and volume and contain the same amount of water at different temperatures (see the figure below). Into each cup, a drop of green ink was added. Eventually the water glasses were painted an even light green. Which glass became evenly painted first? (B)



(A) In Cup 1

(B) * In Cup 2

Question 24.2

The reason your answer is: (B)

(A) Low temperature stops the movement of the ink.

(B) * Ink particles moving faster at a higher temperature.

(C) Cold temperature accelerates the particle velocity.

(D) The high temperature causes the particles to expand.

APPENDIX B: PRE- AND POSTTEST CONTENT KNOWLEDGE QUESTIONNAIRE ALIGNMENT WITH CONCEPTUAL FRAMEWORK

Conceptual framework	Components	Questionnaire items
Form of access	Submicroscopic	3, 10, 12,13,14,15
	Macroscopic	4,5,9, 16, 23.1, 23.2, 25.1
Bridges	Submicroscopic/macroscopic	1, 2, 6, 7, 10, 11, 17, 18, 19, 20, 24, 25.2

Note. The numbers refer to those in the questionnaire in Appendix A