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Exploring Grade 11 Students' Conceptual Pathways of the Particulate Nature of Matter in the Context of Multirepresentational Instruction

Emine Adadan,[1] Kathy Cabe Trundle,[2] Karen E. Irving[2]

[1]*Department of Secondary School Science and Mathematics Education, Faculty of Education, Boğaziçi University, Bebek, Istanbul 34342, Turkey*
[2]*School of Teaching and Learning, College of Education, The Ohio State University, Columbus, Ohio*

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Abstract: This study investigated the conceptual pathways of 19 Grade 11 introductory chemistry students (age 16–17) as they participated in a multirepresentational instruction on the particulate nature of matter (PNM). This study was grounded in contemporary conceptual change theory, in particular, research on students' conceptual pathways that focuses on the interaction between students' existing conceptions and instruction, which might give rise to observing multiple paths. This mixed method study combined a quantitative research design with qualitative data collection and analysis methods. Data were collected through open-ended questionnaires, interviews, and document analysis to portray the patterns of students' conceptual pathways of the PNM from pre to postinstruction to 3 months after the instruction. An interpretive analysis of the qualitative data revealed six different conceptual pathways varying between radical progress and no additional progress (stable) after the multirepresentational instruction and between stable (no change) and full decay over a 3-month period following the instruction. The identified patterns of conceptual pathways provide information about the manner in which conceptual change occurred, as well as suggest potential implications for instructional practices. © 2010 Wiley Periodicals, Inc. J Res Sci Teach 47: 1004–1035, 2010

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An extensive body of research concerning students' nonscientific conceptions, or alternative conceptions, has accumulated over the past three decades (Duit, 2006). Researchers frequently call attention to the fact that students come to science classes with a broad range of conceptions of diverse phenomena. These conceptions typically differ from the scientific views and usually are resistant to change, despite instruction (Duit, 1999; Vosniadou, 1994). In addition, students' existing conceptions associated with the physical phenomena considerably shape their subsequent science learning (National Research Council [NRC], 2007; Taber, 2008). Indeed, the mere documentation of students' alternative conceptions within a domain of science informs teachers and researchers about the features of such conceptions, but only doing so appears to be inadequate for the improvement of science learning. The very nature of students' alternative conceptions requires carefully designed and implemented instructions for conceptual change learning (Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou, 2001). Given the significance of understanding the mechanisms of conceptual change in terms of its potential implications for science instruction, recent research has focused on the examination of the nature of conceptual change (Treagust & Duit, 2008). In particular, researchers are concerned about how instruction interacts with students' existing conceptions, and they have called for the exploration of conceptual progression around specific concept areas over time (Taber, 2008).

Instruction designed to promote conceptual change usually requires substantial time and effort on the part of the teacher and learners. Thus, the durability of students' scientific conceptions constructed in the

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Correspondence to: E. Adadan; E-mail: emine.adadan@boun.edu.tr
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context of a particular instruction appears to be critical for supporting the development of new scientific conceptions (Georghiades, 2000). Researchers offered different teaching pedagogies (e.g., cognitive conflict approach, particle models, etc.) for promoting students' understanding of the particulate nature of matter (PNM) (Buck, Johnson, Fischler, Peuckert, & Seifert, 2001). *National Science Education Standards* (*NSES*) suggest utilizing multiple representations (MRs) along with oral and written discourse in the inquiry context for teaching of the particle ideas (NRC, 1996, p. 177). Respectively, research into MRs indicates that students who are able to connect multiple modes of representations and translate them into one another are more likely to build scientific understandings of natural phenomena (Adadan, Irving, & Trundle, 2009; Ainsworth, 1999; Kozma, 2003).

Theoretical Framework

Meaningful science learning entails conceptual understanding rather than rote memorization. Students who develop conceptual understandings of certain concepts typically construct well-connected and hierarchically arranged conceptual frameworks, as opposed to having isolated pieces of information (Mintzes & Wandersee, 1998). Some researchers view learning of a new concept as either integration into an existing knowledge framework (*conceptual growth*) or fundamental reorganization of existing knowledge to fit the new concept into the framework (*conceptual change*) (Treagust & Duit, 2008).

The theory of conceptual change learning proposed by Posner, Strike, Hewson, and Gertzog (1982) recognized only strong restructuring in learners' alternative conceptions, namely, accommodation, as conceptual change, ignoring the value of weak restructuring (assimilation) in learners' existing conceptions (Hewson, 1981). Posner et al. (1982) introduced four conditions to be fulfilled for accommodation: *dissatisfaction* with an alternative conception; then, a scientific conception has to be *intelligible*, *plausible*, and *fruitful*. This theory suggested that the status of a scientific conception has to be raised as the relative status of an alternative conception is lowered in students' mind for conceptual change (Hewson & Thorley, 1989). The studies on conceptual change learning by Posner et al. (1982) and others (e.g., Hewson, 1981; Hewson & Thorley, 1989, among others) informed the study in terms of interpreting the status of the participants' conceptions. However, research evidence presented in this study and others (e.g., Driver, Asoko, Leach, Mortimer, & Scott, 1994) indicated that conceptual change learning that involves the replacement of nonscientific conceptions with the new ones neglects the coexistence of multiple conceptions in students' conceptual frameworks as being "stable and coherent explanatory schemes" (Taber, 2000, p. 399). In addition, Posner et al. (1982) argued for the sudden replacement of an alternative conception by a scientific one. Yet, this study did not support that particular notion. Rather, the current study is heavily grounded in the conceptual development view, where conceptual change is portrayed as a slow and gradual process, involving constant *enrichment* and *revision* in students' existing conceptual frameworks (Vosniadou, 1994).

Vosniadou (1994) put forward framework theories that include students' basic epistemological and ontological presuppositions and refer to a cognitive system that individuals create to interpret their observations of the natural world. A framework theory is an explanatory system with some coherence, but frequently diverges from a scientific theory in terms of lacking the systematicity, abstractness, and social nature (Vosniadou, 2003). Students also build specific theories from their everyday experiences or through instruction to explain a particular phenomenon (e.g., heat, force) (Vosniadou, 1994). These specific theories are often constrained by a few entrenched presuppositions within the framework theory that usually hinder the construction of a scientific understanding (Vosniadou et al., 2001).

Vosniadou (1994) maintained that conceptual change learning usually fails when the change in an alternative conception requires revision of presuppositions, and in such cases researchers are likely to observe inconsistency, inert knowledge, and alternative conceptions. Vosniadou (2003) asserted that as students are introduced to scientific knowledge, the structure of their initial explanatory framework loses its stability and starts being reorganized by incoherent context-dependent explanations that are delineated with "inert knowledge" (p. 395). In addition, Vosniadou et al. (2001) referred to instruction induced alternative conceptions as *synthetic models*. In fact, these hybrid models derive from students' attempts to reconcile scientific views they encounter during instruction with entrenched presuppositions they develop based on their daily life experiences (Vosniadou & Brewer, 1992). Students usually are not aware of holding such presuppositions that constrain their reasoning (Vosniadou et al., 2001). Thus, instructional efforts for conceptual change need to involve not only the change in alternative conceptions but also the development of metaconceptual awareness (Duit, 1999; Georghiades, 2000). According to Hennessey (2003), metacognition refers to individuals' *inner awareness* about their processes of learning, involving what they know (content knowledge) and their contemporary cognitive state. In the current study, the students were not explicitly taught metacognitive strategies during the instruction, but journal prompts and the questions included in the activity sheets were generated to implicitly motivate their metacognitive thinking.

Students' Alternative Conceptions of the PNM

The PNM is the most central concept in the science curriculum in terms of its potential to provide a basis for explaining a variety of topics in chemistry, such as chemical change, dissolution, phase changes, chemical bonding (Harrison & Treagust, 2002; NRC, 1996). Research indicated that students' alternative conceptions about the nature and properties of matter are evidently rooted in the presuppositions that implicitly derived from their indirect observation of and spontaneous everyday interaction with a number of phenomena (Pozo & Gómez-Crespo, 2005; Talanquer, 2009; Vosniadou & Brewer, 1992). Nonetheless, researchers also associated students' poor understandings of the PNM with ineffective instruction (Johnson, 1998), misrepresentation of the PNM in the science textbooks (Adbo & Taber, 2009; Harrison & Treagust, 2002), and teachers' lack of understanding of the PNM (Gabel, 1993).

While making sense of the macroscopically observed phenomena, students need to understand that matter is composed of particles that are in continuous motion with a vacuum in between them, and that electrostatic forces keep the particles together at the solid and liquid state. However, research consistently revealed that students' erroneous representations of matter as being smooth, continuous, and static particularly at the solid state are based on how they perceive the physical appearance of substances (Johnson, 1998; Pozo & Gómez-Crespo, 2005; Talanquer, 2009). Therefore, students' ideas about the PNM could change with respect to the context of task (e.g., dissolving, melting) or the forms of substance (e.g., solid, liquid) (Nakhleh, Samarapungavan, & Saglam, 2005). In addition, studies have shown that many students develop such hybrid models of matter that reflect macroparticulate features in which particles appear to be embedded into continuous matter (Johnson, 1998; Nakhleh et al., 2005; Novick & Nussbaum, 1981). Respectively, students at all grade levels frequently do not believe in the notion of the empty space between the particles of matter (Buck et al., 2001; Talanquer, 2009), which is probably due to holding the presupposition that all empty spaces are filled with air. This presupposition could also have links with students' failure to perceive gases as being substances (Johnson & Papageorgiou, in press).

Because students usually view the liquid state as transitional between the solid and gas state, they tend to represent the spacing between particles of liquids as intermediate compared to solids and gases (Adadan et al., 2009; Adbo & Taber, 2009; Johnson, 1998). Drawing on the surface features of substances, students tend to attribute such properties as color, softness, hardness, or physical state change to the individual particles, as opposed to perceiving physical properties of matter as collective behavior of particles (Buck et al., 2001; Griffiths & Preston, 1992; Talanquer, 2009). Although the change in intermolecular distances of substances, when heated or cooled, has nothing to do with the change in the size of particles, some students believe in the expansion of atoms themselves on heating (Adbo & Taber, 2009). Students could also consider the change in the size of the particles as the substance undergoes a phase change. For example, Griffiths and Preston (1992) found that some students view the molecules of ice as the largest and the molecules of water vapor as the smallest in size.

Students often perceive the three forms of matter (solids, liquids, and gases) as fundamentally separate types of matter probably due to lack of understanding about the connection between the electrostatic forces acting among the particles and the physical states of matter (Johnson & Papageorgiou, in press). However, among the aspects of the particle theory of matter, the notion of electrostatic forces acting among the particles was reported to be the most conceptually demanding, and students frequently encounter problems in recognizing the similarities and distinctions between the intermolecular forces and covalent bonding (Adadan et al., 2009; Johnson, 1998; Talanquer, 2009). In the same manner, Liu and Lesniak (2005) stated that "explaining and predicting matter and changes using bonding theories represents . . . the highest level of matter concept development" (p. 446).

Models, Modeling, and Multiple Representations in Teaching Science

Models, as a critical aspect of scientific inquiry, are viewed as valuable instructional tools and are utilized in science classrooms in multiple ways (Treagust, Chittleborough, & Mamiala, 2002). Teachers integrate models into their instruction as a means of explaining abstract concepts or unobservable phenomena, as well as improving understanding and communication among students. Mental models developed by students are their personal cognitive representations, which are accessible to teachers through students' external representations of their understanding of the phenomena in various modes, such as verbal (oral discourse, writing), visual (drawings, animations, simulations), or symbolic (equations, formulae) (Boulter & Buckley, 2000). Many high school students build their expressed models based on macroscopic features of the observed phenomena, frequently perceiving models as exact replicas of the real thing, and few students believe that models represent ideas or abstract entities (Grosslight, Unger, Jay, & Smith, 1991).

Ainsworth (1999) suggested that MRs provide diverse opportunities for students to construct the same knowledge from distinct perspectives. In addition, utilizing the inherent characteristics of the familiar representation may facilitate the interpretation of another more abstract representation. MRs, given the essential role of explicit teaching about the associations among the representations, help students create a deep understanding of a domain. Along the same line, the teaching and learning of chemistry requires three levels of representation: macroscopic (e.g., rusted iron); submicroscopic (e.g., formation of ferric and oxygen ions when iron is exposed to air and moisture); and symbolic (e.g., Fe_2O_3) (Gabel, 1993; Johnstone, 1982). Unlike scientists in many other fields, chemists use representations to illustrate "*unseen* entities and processes" that occur during the chemical inquiry (Kozma, Chin, Russell, & Marx, 2000, p. 107, emphasis added). Accordingly, developing a full understanding of a chemical phenomenon requires the ability to move between the three levels of its representation (NRC, 1996). Although chemists are able to employ multiple modes of representations with ease, students find the task of managing multiple modes of representations highly challenging (Kozma, 2003).

Mayer (2001) viewed multirepresentational learning as "learning from words and pictures" (p. 3). He acknowledged that MRs potentially give rise to building connections between the different features of the same phenomena, because each mode of representations provides learners twice as much occasion to make sense of the incoming information.

In the present study, verbal forms of representations include students' oral and written explanations of the physical phenomena at the macroscopic and the submicroscopic level. The pictorial forms of representations involve student-generated drawings, dynamic molecular animations, and the static particle models of the three states of matter.

Research on Learning Progressions or Conceptual Pathways

Researchers who track student learning across time use the phrases such as *learning progressions*, *learning pathways*, or *conceptual pathways*. Smith, Wiser, Anderson, and Krajcik (2006) described *learning progressions* as successively more sophisticated ways of reasoning about a topic that follow one another as students learn about and explore a topic over a period of time. Rea-Ramirez (2008) stated that students rarely develop the target concept in one large step. However, they generate multiple intermediate ideas as they progress toward the target concept. Thus, the sequential outline of ideas from preinstructional conception to the development of a target concept provides a *learning pathway.* In addition, Scott (1992) characterized *conceptual pathways* as "learning routes along which students pass in developing understanding in any domain of science" (p. 221). In this study, the term, *conceptual pathways*, was utilized to refer to the conceptual understanding path that students' followed starting from pre to postinstruction to 3 months after the instruction.

Regardless of which labels were used for *learning progressions*, researchers shared similar views concerning the features of such a notion: (a) Learning progressions vary student to student with respect to existing conceptions they hold or several other factors (e.g., the context, task, and support), giving rise to observing multiple paths, and (b) Learning progressions are not closely related to cognitive development but are largely shaped by interaction between instruction and students' existing conceptions (Lehrer & Schauble, 2009; NRC, 2007; Rea-Ramirez, 2008; Scott, 1992; Smith et al., 2006; Stevens, Delgado, & Krajcik, in press). Learning progressions provide promising learning opportunities for students to develop integrated conceptions of a few fundamental ideas in science by giving attention to the alignment of the content, instruction, and assessment strategies (Stevens et al., in press). Moreover, Duncan and Hmelo-Silver (2009) stated that learning progressions are bounded by upper and lower anchor, and upper anchor describes what students are expected to do by the end of progression (e.g., in the present study, it refers to a scientific understanding of the PNM), whereas lower anchor represents the prior knowledge or students' level of understanding as they enter the progression (e.g., in this study, it stands for students' type of understandings on the prequestionnaire).

Lehrer and Schauble (2009) put forward that learning progressions should describe learning under specifically designed instruction; otherwise, learning progressions just depict what students are able to do in the current conditions of teaching, which has quite low expectations for learning. More specifically, Smith et al. (2006) pointed out that the development of an understanding of the PNM is a challenging process that happens gradually and requires nontraditional instruction (p. 26).

Duncan and Hmelo-Silver (2009) noted that learning progressions by their very nature are hypothetical. For example, Smith et al. (2006) proposed a hypothetical learning progression for the topic of matter and atomic molecular theory based on the available research as well as providing sample assessment items for the learning progression. There are others articles that report hypothetically developed learning progressions in various domains (e.g., Duncan, Rogat, & Yarden, 2009; Stevens et al., in press). However, Duncan and Hmelo-Silver (2009) emphasized the need for empirical research on the development of student thinking and learning progression in a certain domain. In this respect, research on learning progressions appears to be important for understanding how a particular instructional intervention and individual differences (e.g., existing knowledge) act together in the development of scientific understandings of concepts. Few studies on learning progressions have empirically looked into the development of students' understandings about diverse phenomena over a period of time in the context of the promising interventions (Malandrakis, 2006; Petri & Niedderer, 1998; Songer, Kelcey, & Gotwals, 2009; Trundle, Atwood, & Christopher, 2007; Tytler, 1998a,b). Learning progressions research concerning the topic of the PNM involved either cross-age studies (e.g., Liu & Lesniak, 2005; Novick & Nussbaum, 1981; Pozo & Gómez-Crespo, 2005, among others) or studies that examined the immediate efficacy of the use of visual tools or MRs on students' understanding of the PNM (e.g., Kelly & Jones, 2007; Singer, Tal, & Wu, 2003; Williamson & Abraham, 1995, among others). Yet, these studies have usually provided statistical evidence for student learning of the PNM. Just a few studies have extensively explored students' learning progressions of the PNM in various instructional contexts over a period of time (Johnson, 1998; Margel, Eylon, & Scherz, 2008; Snir, Raz, & Smith, 2003). Thus, additional research is needed, particularly studies that focus on examining the patterns of progression in students' understandings of the PNM as they engage in a particular instruction (e.g., multirepresentational instruction).

Purpose of the Study

The main purpose of the study was to identify and describe Grade 11 (age 16–17) introductory chemistry students' conceptual pathways of the PNM from pre to postinstruction to 3 months after the multirepresentational instruction on the PNM. The subsequent goal of the study was to investigate the efficacy of the multirepresentational instruction on promoting change in students' conceptual understandings of the PNM and maintaining newly constructed scientific understandings. The following research questions guided this study:

(1) How do Grade 11 students' types of conceptual understandings of the PNM differ from pre to postinstruction and from post to 3 months after completion of the multirepresentational instruction on the PNM?
(2) What are the patterns of Grade 11 students' conceptual pathways of the PNM from pre to postinstruction to 3 months after completion of the multirepresentational instruction on the PNM?

Research Design

This mixed method study combined both a one-group quasi-experimental design with a pre, post and delayed postquestionnaire and qualitative data collection and analysis procedures (Tashakkori & Teddlie, 1998). This study consisted of more than two comparable assessment measures that may make it appear to be a longitudinal study. However, the short duration of the study (about 5 months from the beginning to the end) disqualifies the study as a true longitudinal design, which some researchers consider to take place over at least a 1-year period of time (White & Arzi, 2005).

Participants

This study took place in a comprehensive 4-year high school located in a suburban area of a large city in the Midwestern United States. At the time of the study, the total enrollment at the high school was 1,586 students. The student population was fairly homogenous, with 80% of the school population being White, and 20% of the students coming from various other ethnic and racial backgrounds. The participants of the study were selected on a voluntary basis. The participants included 19 Grade 11 students who were enrolled in an introductory chemistry course. The sample of 19 students with age 16–17 consisted of 9 males and 10 females. Every student had completed at least one life science course and freshman physical science, but no one had previously taken either a physics or chemistry course. In addition, the teacher who taught this group of students had 4 years of teaching experience. She held a Master of Education degree in science education and was certified to teach both high school chemistry and biology courses.

Data Collection

Although researchers usually assessed students' learning progressions of the PNM through interviews (e.g., Johnson, 1998; Malandrakis, 2006; Snir et al., 2003), other data sources also were used for the same purpose such as drawings along with verbal explanations (Margel et al., 2008; Singer et al., 2003; Williamson & Abraham, 1995), written performance tasks (Smith et al., 2006). In this study, qualitative data were collected from diverse sources (e.g., questionnaires, interviews, other documents) in multiple modes (e.g., pictorial, verbal). The research questions were mainly addressed through coding and analyzing the primary data sources of open-ended questionnaires and student interviews. In addition, the collected documents (e.g., activity sheets and journal entries) were carefully read, and the relevant excerpts were selected as evidence to provide a more complete picture of students' conceptual understandings of the PNM. Data that reflected the views of a small group (such as documents produced during small group work—activity sheets) provided insight into the classroom proceedings, but were not useful to the researchers when characterizing the conceptual pathways of individual students. The main data sources are briefly described in the following sections.

Questionnaire. The open-ended questionnaire, entitled the Nature of Matter–Diagnostic Questions (NMDQ), was primarily derived from written tasks used in previous research (Williamson, 1992). All utilized tasks were rewritten with respect to the objectives of the current study, and new questions were added. Previous research suggested that drawings provide rich data about students' understanding of science concepts and reveal alternative conceptions (Dove, Everett, & Preece, 1999; Van Meter, Aleksic, Schwartz, & Garner, 2006). In addition, drawings can be used to explore students' understanding of rather abstract concepts (Dove et al., 1999), one of which could be the PNM. Thus, almost all tasks in the NMDQ included pictorial particulate representation portions (drawings) coupled with open-ended questions that sought explanation for students' pictorial representations of the given phenomena (e.g., the diffusion of food coloring; see Appendix A). Each aspect of the particle theory of matter addressed in the instruction was assessed at least twice in different contexts to ensure that students' understanding of the key aspects of the PNM was not confined to the context (Jimenez Gomez, Benarroch, & Marin, 2006). The nature of 10 tasks included in the NMDQ can be seen in Table 1. The content validity of the questionnaire was established by a panel of experts, including a science educator, a postdoctoral researcher, and a doctoral candidate, all of whom were specialized in chemistry. The participants took the NMDQ questionnaire three times: 2 weeks

Table 1
The content and focus of questionnaire tasks

Tasks	Description of Context of the Task
1	A piece of iron, a glass of water, and an air filled balloon were pictorially represented at the macroscopic level; students were asked to pictorially represent how each of these materials look, if students would be able to see what happens inside these materials with a powerful magnifying device
2	Given that a flask is filled with air, students were asked to pictorially represent the air inside the flask before and after some amount of air has been pumped out
3	Given that water exists in three physical states, students were asked to both pictorially represent and verbally explain the arrangement of and distances between particles in three states of matter
4	Given that sugar dissolves in water, students were asked to both pictorially represent and verbally explain the dissolution of sugar in water at the submicroscopic level
5	Given that a clear plastic cup is half filled with water, and a few drops of food coloring is added into it, students were asked to both pictorially represent and verbally explain what happens to the food coloring in water over time
6	Given that air and a colored gas are placed in a container separated by a valve, students were asked to both pictorially represent and verbally explain what happens at the submicroscopic level after the valve is opened
7	A closed flask containing air was represented at the particle level; students were asked to both pictorially represent and verbally explain the behavior of air particles inside the flask after air has been cooled down until it liquefies
8	A flask containing some solid was represented at the particle level; students were asked to both pictorially represent and verbally explain the behavior of particles of a solid after a solid has been heated until it becomes a liquid
9	A syringe consists of some amount of gas, and the plunger of the syringe is pushed in without removing any gas; students were asked to pictorially represent the two situations in terms of what happens before and after the plunger of syringe is pushed in and verbally explain what properties of matter allow compression of gases along with their reasoning
10	A flask containing the particles of oxygen is represented at the submicroscopic level; students were asked to explain what there is between the particles of oxygen along with their reasoning

before the instruction, 1 week following the instruction, and 3 months after students completed the postquestionnaire.

Interview. The postinstruction interviews were conducted with the eight students who were purposefully selected with respect to their responses on the postquestionnaire. Students whose responses displayed alternative conceptions of the PNM were particularly interviewed to elicit their understandings of the given phenomena. Students who were interviewed belonged to the following type of conceptual understandings after the instruction: scientific understanding (3); scientific with alternative fragments (5). In the interviews, students were asked the same questions as on the postquestionnaire, and when needed, students' ideas were probed using follow-up questions.

Data Analysis

The constant comparative method (Glaser & Strauss, 1967) was employed in the data analysis. The data analysis scheme used in this study was adopted from Trundle, Atwood, and Christopher (2002) and Trundle et al. (2007). The earlier research reports (e.g., Johnson, 1998; Novick & Nussbaum, 1981; Williamson & Abraham, 1995) were utilized to describe the criteria for a scientific understanding and identify the possible alternative conceptions that participants might have. This information assisted the development of a "partial framework" (Glaser & Strauss, 1967, p. 45) for analysis. A coding sheet and coding scheme were designed based on the partial framework (see Adadan, 2006). Table 2 includes the descriptions of the codes (coding key). The researchers used the same coding sheet and the coding scheme for analysis of student responses to the pre, post and delayed postquestionnaire and the postinterview. Each time the researchers looked for alignment of participants' responses with the coding scheme. Because the constant comparative method allowed for "joint coding and analysis" of the data (see Glaser, 1965, p. 437), the codes from postquestionnaire and postinterview were compared, and the joint codes were recorded. For each data

Table 2
Coding key

Code	Meaning of Code
SciPart	Matter is made up of particles
SciArr	Particles of solids are arranged in symmetric arrays. Particles of liquids and gases are arranged randomly
SciDist	There are large distances between the particles of gases, but the distances between the particles of solids and liquids are relatively similar
SciMove	Particles of solids vibrate at a fixed point; liquid particles have flexibility of movement, and gas particles freely move toward all directions
SciForce	There are strong electrostatic forces between the particles of a solid. These forces weaken as a solid turns into a liquid, then, a gas
SciEmpty	Nothing exists between the particles of matter
SciUni	Particles of a gas are uniformly distributed even if half of the gas is released
SciDns	The density of gas particles changes if a gas is added or released from the closed container. The density of matter changes when it undergoes a phase change such as melting or condensation
AltPart	Matter is continuous
AltArr	Particles of a solid are randomly arranged. Particles of a liquid are regularly arranged
AltDist	The relative spacing among particles of a liquid is considered as in between the distances among particles of a solid and a gas
AltMove	The particles of a solid either do not move or move very fast
AltForce	The intermolecular forces are considered as intramolecular. Or, physical changes are considered to be a chemical change, such as mixing of liquids or gases
AltEmpty	Air or some other material(s) exists between particles of matter
AltUni	Gas particles are not uniformly distributed, when half of the gas is pumped out. Particles of a solid or liquid are accumulated at one spot in another liquid even after dissolving or mixing occurs
AltDns	The density of a gas does not change when it turns into a liquid or when it is compressed without releasing any gas from the syringe
AltColor	Particles of colorless substance such as water (or air) become colored by a colored substance such as food coloring (or colored gas)
AltBond	The solid lines (bonds) exist between particles of solids and liquids
AltSize	Size of the particles increase/expands as the gas turns into a liquid then a solid
AltDiss	Water absorbs particles of sugar, or sugar melts
NoCU	Not enough and clear evidence to code the response

collection point, the emerged codes were categorized and compared to the criteria set for the types of conceptual understandings (see Table 3). Then, each participant was assigned a type of understanding that holistically revealed the codes or the joint codes (see Table 3). The issue of using the codes from a single data source and the joint codes from multiple sources was strictly considered, and the decision was made accordingly. In case of any doubt, a less scientific type of conceptual understanding was assigned.

Table 3 provides the description of criteria established for five types of conceptual understanding categories (see Adadan et al., 2009). A fragment in this study refers to one of the eight critical aspects of the PNM. For example, consistently offering evidence for an understanding that electrostatic forces keep the particles of solids and liquids together is a more complex knowledge piece than the notion of "p-prim" (diSessa, 1993, p. 111). An alternative fragment in this study implies a specific alternative conception of the PNM (e.g., an understanding that air exists between particles of matter).

For research question 1, the frequency of students' types of conceptual understandings at three data collection points was found. In addition, numerical values were assigned to each type of conceptual understanding categories from 0 (Alternative Fragments) to 4 (Scientific Understanding) (see Table 3). Using the numerical data, a nonparametric statistics of the Sign Test was utilized for the paired categories of conceptual understandings (pre–post and post–delayed post) (Siegel & Castellan, 1988).

For research question 2, individual students' types of conceptual understandings were compared across three data collection points to identify the patterns of students' conceptual pathways of the PNM. The types of conceptual understanding categories were considered to be on a continuum from the least scientific (Alternative Fragments) to the most scientific (Scientific Understanding) (see Table 3), and the extent of progression/regression/no change each student exhibited on this continuum from pre to postinstruction and from post to 3 months after the instruction revealed the pattern of his/her conceptual pathway of the PNM.

Table 3
Types of conceptual understandings and criteria

Categories of Conceptual Understandings	Criteria
Scientific understanding	Must include all of the following scientific conceptual understanding criteria: Matter consists of enormous number of tiny *particles* Particles of solids, liquids and gases are in constant *motion* There are *electrostatic forces* that act between the particles of solids and liquids, whereas negligible forces exist between the particles of gases Particles of solids are arranged regularly, whereas particles of liquids and gases are *arranged* randomly Particles of solids and liquids are *spaced* similarly, but there are large spaces between the particles of gases Particles of gases are *uniformly distributed*. Particles of solids and liquids are uniformly distributed when they dissolve or mix The *density of gas* particles changes if a gas is added or released from the closed container. The density of matter changes when it undergoes a phase change such as melting or condensation A vacuum (*empty space*) exists between the particles of matter
Scientific fragments	Must include scientific understanding criteria of "Matter consists of enormous number of tiny particles" and includes a subset of the other seven scientific understanding criteria, but not all of them
Scientific with alternative fragments	Must include scientific understanding criteria of "Matter consists of enormous number of tiny particles", and includes a subset of the other seven aspects of the PNM with at most three alternative criteria (see alternative fragments)
Alternative with scientific fragments	Include a subset of the alternative conception criteria indicated in alternative fragments section with at most two scientific aspects of the PNM
Alternative fragments	Include a subset of conceptual understandings that are in conflict with scientific aspects of the PNM with no fragments of scientific understanding. The alternative conceptions emerged from the data follows: Matter is continuous The particles of a solid either do not move or move very fast When two liquids or two gases physically mix, a new substance forms Solid lines exist between particles of a solid and/or a liquid to show that they are connected one another Particles of a liquid are regularly arranged with lines between particles Liquid particles are not closely packed as much as particles of a solid Particles of a gas accumulate either at the top or the bottom of the container when half of the gas is released from the container Two gases do not uniformly mix because two gases have the same density Particles of colorless substance such as water (or air) are dyed by colored substance such as food coloring (or colored gas) When an amount of a gas turns into a liquid, the gas becomes heavy Air or other materials exist(s) between particles of matter Water absorbs the sugar molecules when sugar dissolves in water. OR Sugar melts when it is put into water Size of the particles increase as the gas turns into a liquid, then, a solid One substance takes over or covers another one due to its heaviness

Twenty-five percent of the responses to the NMDQ on the pre, post, and delayed postquestionnaire and the interview transcripts (for students who were interviewed) were randomly selected. The first author and another science educator who was not involved in the research project, each independently coded the selected data. The agreement for students' types of conceptual understanding categories was calculated at 94%.

The Framework of Instructional Intervention

The multirepresentational instruction was designed by integrating several teaching suggestions derived from the current research on student science learning (Driver et al., 1994; NRC, 1996; Smith et al., 2006;

Tasker & Dalton, 2006; Van Meter et al., 2006; Vosniadou et al., 2001). Since the multirepresentational instruction was fully described in a previous study (Adadan et al., 2009), only the basis of the instruction is provided here.

The instruction lasted 12 class periods and was intended to explicitly address students' common alternative conceptions about the aspects of the particle theory of matter as well as attaining the physical science content goals suggested by the *NSES* for high school students. The concepts comprising the particle theory of matter were introduced to the students in the following sequence: the PNM, the arrangement of particles, the distances between the particles (also density of particles), the motion of particles (also uniform distribution of particles), the existence of a vacuum among the particles, and the existence of electrostatic forces among the particles. These concepts were arranged with respect to their degree of priority in building the subsequent concepts (Smith et al., 2006; Vosniadou et al., 2001), and they were offered in three physical states, considering that students do not develop the particle ideas equally across all physical states (Nakhleh et al., 2005; Pozo & Gómez-Crespo, 2005).

The *NSES* (NRC, 1996) place substantial emphasis on active construction of ideas through inquiry, as well as the development and use of science process skills in everyday contexts. Vosniadou et al. (2001) acknowledged that "learning is not an individual, but a social affair" (p. 382). Teachers need to encourage students to share and negotiate their understandings of the observed phenomenon in the classroom (Driver et al., 1994). Thus, the participants of the study predicted, observed, inferred, and questioned the submicroscopic occurrences of 10 different physical phenomena by working in groups with their peers (see Adadan et al., 2009). Based on their macroscopic observations, each group of students, as a consensus view, developed both verbal and pictorial representations to account for what happened at the submicroscopic level. Then, each group transferred their pictorial particle models that they generated for the same observed phenomenon in different time intervals to poster-sized whiteboards and presented their pictorial models to the class along with their verbal explanations about the submicroscopic occurrences of the phenomenon. The teacher sometimes stopped the students and asked for further clarification about their drawings and explanations. Once the presentations were finished, the students discussed and came to a consensus on the best verbal and pictorial representation of the observed phenomenon.

Vosniadou et al. (2001) claimed that "if students think in terms of models, then instruction that is model-based, rather than only linguistically . . . based, may have a better chance of producing conceptual change" (p. 394). During every class period, a static particle model transparency was projected on a screen at the front of the classroom to be used as a visual reference during small-group or whole-class discussions. Following the whole class discussions, the students also viewed the online simulations of three macroscopically observed phenomena, such as the motion of particles in three states of matter, the dissolution of a solid, and the diffusion of gases, which are available on the World Wide Web (see Adadan, 2006, for websites). Each animation clip was played twice, while directing students' attention to the key aspects of the animation. Afterward, students compared and contrasted their own drawings with the animation they had just viewed (see Tasker & Dalton, 2006), and they had the opportunity to revise their pictorial particle representations or verbal explanations if needed.

Prain (2006) contended that scientifically literate students need to know not only how to apply science concepts to everyday situations but also develop oral and written communication skills to make their ideas available to others. Thus, activity sheets were provided to students for each phenomenon so they would be able to communicate their reasoning on paper both verbally and pictorially (see Adadan, 2006, for activity sheets). The pictorial and verbal information about the aspects of the particle theory of matter was included in activity sheets to assist students in creating their own representations of the observed phenomenon (see Van Meter et al., 2006).

The instruction also offered students an opportunity to express their mental models of the phenomenon and to compare their current models with the initial ones (Vosniadou et al., 2001). Following the activity on a particular aspect of the particle theory of matter (e.g., the motion of particles), students were given six prompts to write a one-page handwritten journal. A copy of student activity sheets and journal entries were collected. The teacher and the researcher read these documents for formative assessment purposes as soon as students handed them in, which informed the planning of the instruction for the next class period (see Black & Wiliam, 1998).

After the completion of the instruction, the aspects of the particle theory of matter were not reinforced/revisited by the teacher while teaching the other topics of chemistry over a 3-month period. That is, the classroom teacher turned back to her regular instruction in which she utilized a lecture approach by integrating relevant lab/hands-on activities into the instruction.

The first author of the study, a science educator, served as the participant observer. She participated in the classrooms, observing students' interactions with their peers during the activities. She also trained the classroom teacher by working one-on-one with her out of class time and by being present in the classroom during instruction to assist its implementation.

Findings

Research Question 1: How do Grade 11 students' types of conceptual understandings of the PNM differ from pre to postinstruction and from post to three months after completion of the multirepresentational instruction on the PNM?

Table 4 summarizes the frequency of students' type of conceptual understandings before, immediately after and 3 months after the multirepresentational instruction. Before the instruction, only 4 of the 19 students whose conceptual understandings were classified as scientific understanding with alternative fragments predominantly showed scientific conceptions, but they still lacked understanding of a few aspects of the PNM. The majority of students (15 of the 19) consistently exhibited numerous alternative conceptions on various aspects of the PNM so that their conceptual understandings were categorized either as alternative understanding with scientific fragments or alternative fragments (see Tables 3 and 4).

Following the instruction, 11 of the 19 students' conceptual understandings displayed a progression to a full scientific understanding of the PNM (see Tables 3 and 4). Yet, 1 of the 19 students whose conceptual understanding was identified as scientific fragments failed to provide an explanation for all eight scientific criteria, indicating no alternative conception in her explanatory framework. Six of the 19 students showed consistent conceptions but a partial scientific understanding of the PNM, meeting the criteria set for scientific understanding with alternative fragments. Despite instruction, one student whose conceptual understanding was identified as alternative understanding with scientific fragments persisted in holding several alternative conceptions with few fragments of scientific conceptions. Three months after the instruction, 7 of the 19 students maintained their full scientific understandings of the PNM.

Table 5 shows the results of the Sign Test statistics. The test statistics on students' pre and postinstructional conceptual understanding scores revealed that 18 of the 19 students changed from holding less scientific understandings of the PNM to holding more scientific understandings of the PNM ($p < 0.01$). Moreover, 5 of the 19 students' postinstructional conceptual understandings of the PNM decayed over a 3-month period, whereas 13 of the 19 students held onto their postinstructional types of conceptual understandings ($p > 0.05$). In summary, the results of the Sign Test statistics were in line with the findings of qualitative analyses, which exhibited considerable alteration in students' preinstructional understandings of the PNM toward more scientific understandings after the instruction, as well as maintenance of their postinstructional conceptual understandings of the PNM over a 3-month period.

Table 4
Summary of students' types of conceptual understandings of the PNM

	Before Instruction		After Instruction		Three Months After Instruction	
Type of Conceptual Understandings	#	%	#	%	#	%
Scientific understanding	0	0	11	58	7	37
Scientific fragments	0	0	1	5	1	5
Scientific with alternative fragments	4	21	6	32	10	53
Alternative with scientific fragments	14	74	1	5	1	5
Alternative fragments	1	5	0	0	0	0
Total	19	100	19	100	19	100

Table 5
The Sign test statistics for changes in students' types of conceptual understandings

Types of Understandings	Pre to Postinstruction	Post to Three Months After the Instruction
Conceptual decay	0	5
Conceptual progression	18	1
No change (stable)	1	13
p	0.000	0.219

Research Question 2: What are the patterns of Grade 11 students' conceptual pathways of PNM from pre to postinstruction to three months after completion of the multirepresentational instruction on the PNM?

Figure 1 shows the patterns of individual students' conceptual pathways of the PNM in tandem with their pseudonyms and the types of understandings that each held at three data collection points. An interpretive analysis of the data revealed the six different patterns of conceptual pathways, which were hierarchically

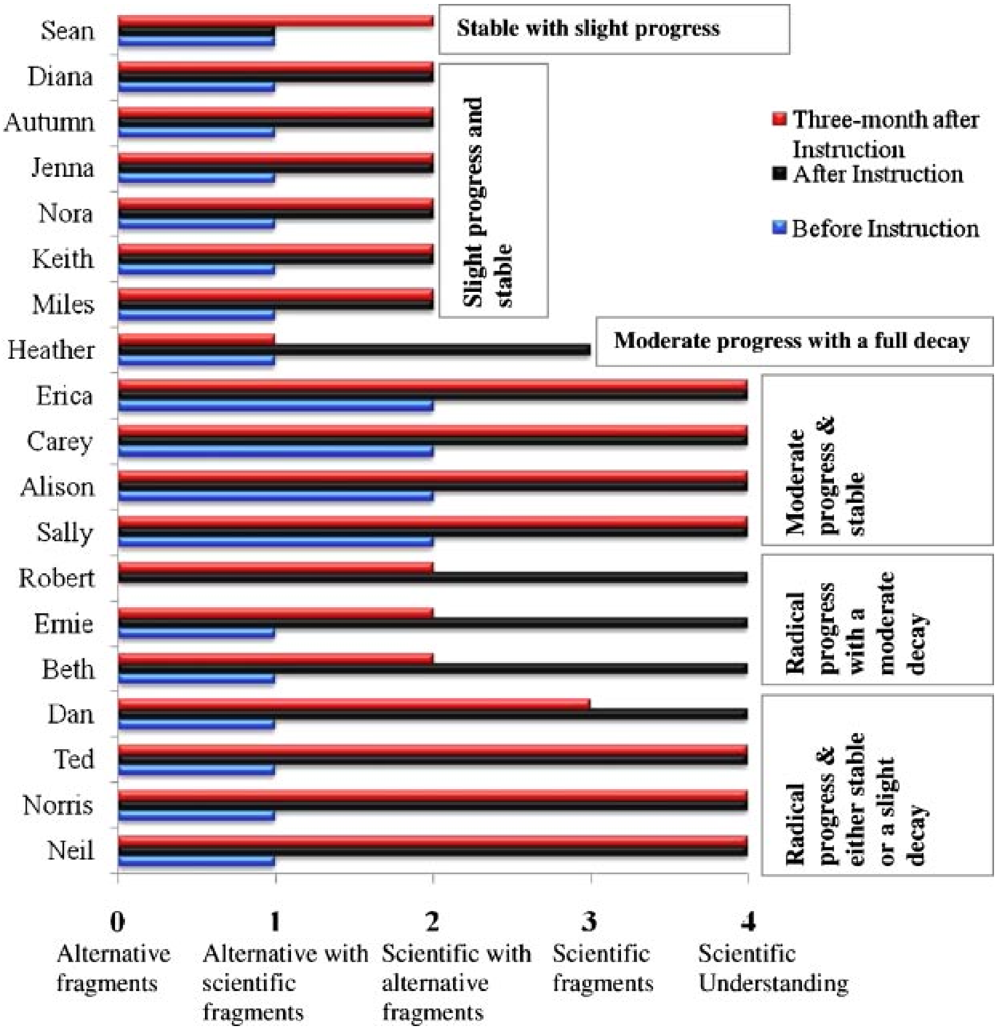


Figure 1. Summary of the patterns of conceptual pathways.

arranged from radical progress (1) to no progress or stable (6). A three-category progression on the types of conceptual understanding of the PNM continuum was identified to be a *radical progress* (see Table 3). As the conceptual progress from alternative fragments category toward scientific understanding decreased, the degree of conceptual progression was recognized to be either *moderate* or *slight*. If students' type of understanding of the PNM indicated persistence with no deterioration/progression over time, this case was considered to be *no change* (stable). In addition, the extent of conceptual decay changed with respect to students' initial types of conceptual understandings. The case of reverting to the initial types of understandings of the PNM over time was considered to be *a full decay*. In the subsequent sections, the unique patterns of conceptual pathways will be defined and depicted by an exemplary case.

Conceptual Pathway 1: Radical Progress and Either Stable or a Slight Decay

The students, namely Neil, Norris, Ted, and Dan, whose conceptual pathways of the PNM indicated the features of radical progress and either stable or a slight decay started the instruction with holding alternative understanding with scientific fragments but they developed a full scientific understanding of the PNM following the instruction. The preinstructional understandings of each advanced by three or more categories (see Table 3 and Figure 1). Three of the four (Neil, Norris, and Ted) students' postinstructional understandings of the PNM remained "durable" (Georghiades, 2000), but one (Dan) of the students' understanding slightly decayed (one conceptual understanding category "regressed," Tytler, 1998a) over a 3-month period.

Excerpts from Neil's responses at three data collection points are presented here as a typical example for the conceptual pathway of "radical progress and stable." (After each statement by participants, codes are provided showing how the particular conception was coded; see Table 2 for a key to the codes.) Before the instruction, Neil provided evidence for understanding the idea that matter consists of a number of particles, but he was not able to show pictorially the distinctive properties of the arrangement of and the spacing between the particles in three states of matter (see Figure 2a). In his representation, the particles were

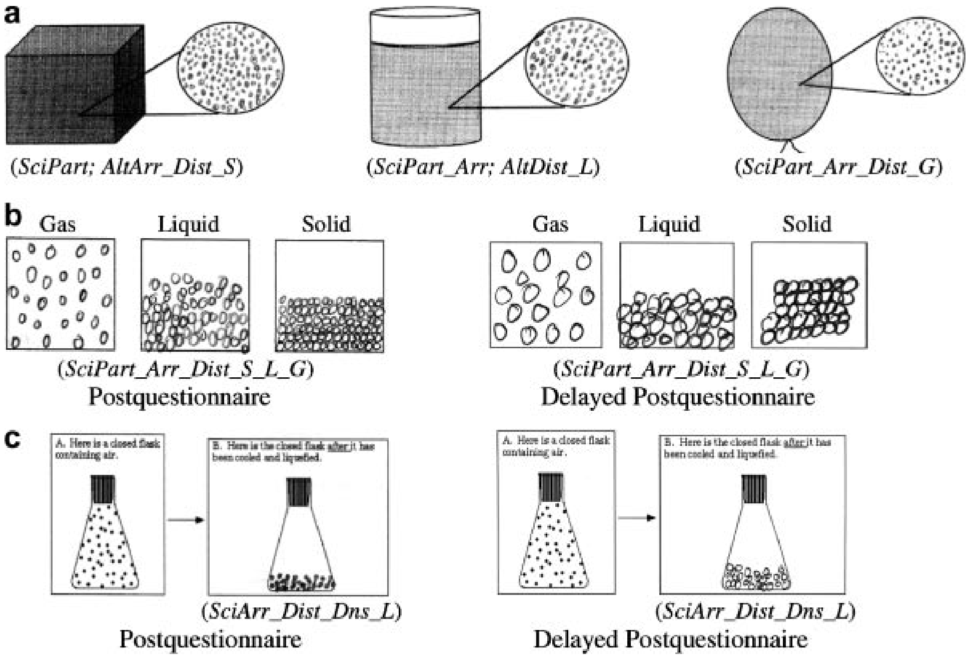


Figure 2. (a) Neil's representation of the three states of matter on the prequestionnaire. (b) Neil's representation of the three states of matter on the post and delayed postquestionnaire. (c) Neil's representation of the condensation of gases.

randomly arranged and looked alike for all three states of matter. The spacing between particles of a liquid and a gas appears to be identical. Neil also believed that electrons exist between the molecules of oxygen, claiming, "The electrons. Since all are negatively charged, they are constantly pushing away from each other" (*AltEmpty_G*). While explaining the melting of solids, Neil said,

> Because a solid is the hardest object other then gas or liquid so it stays all attached together (*NoCU_Force*). Liquids spread apart, I think, because the solid loses its form so the particles aren't enough to attach to each other (*NoCU_Force*).

Neil's use of the phrase "attached together" may have been interpreted that Neil referred to electrostatic forces existing between particles of liquids, but the researchers chose a conservative approach while coding and categorizing codes. Because his explanation was not clear enough, his statement was coded as no conceptual understanding.

Following the instruction, not only was Neil able to illustrate the unique patterns for the arrangement of and spacing between the particles verbally and pictorially, but he also related his explanation to the existing electrostatic forces among the particles. Neil said:

> [See Figure 2b.] Gases are the most spread out of the three phases (*SciUni_Arr_Dist_G*), because there is almost no attraction force between the particles (*SciForce_G*). There are some attraction forces between the particles of liquids so that they are . . . unorganized, but all close together (*SciForce_Arr_Dist_L*). Particles of solids have the most attraction forces of the three phases, so, they are organized and do not lose their shape (*SciForce_Arr_S*).

Neil also explained the diffusion of food coloring by providing a basis for his explanation on the postquestionnaire: "Because molecules of food coloring are constantly moving and rearranging themselves in water (*SciMove_L*), sometimes later food coloring spreads out all around the water molecules (*SciUni_L*)." In response to the task of the condensation of gases, Neil associated the concept of motion of particles to the existing electrostatic forces between the particles (see Figure 2c): "As the molecules are cooled down, the molecules of a gas slows down (*SciMove_L_G*) and molecules become more attracted to each other (*SciForce_L_G*)". Even though Neil did not offer any explanation about the motion of particles of solids before the instruction, he was able to relate the changing attraction ability of electrostatic forces with the change in motion of particles following the instruction:

> Molecules of solids have a greater attraction forces towards each other (*SciForce_S*). As solids melt, particles of solids begin speeding up their vibrating movement (*SciMove_S_L*) and later particles begin breaking off and losing some attraction force between particles (*SciForce_S_L*).

In addition, he showed evidence of believing in the existence of a vacuum between the particles on the postquestionnaire. An excerpt from his journal entry confirmed the assistance of the instruction on his understanding of this particular concept:

> I was confused when I put 50 ml of water into 50 ml of alcohol, and I did not get 100 ml of liquid. Before I never knew what was between the particles of liquids, and what I know now it is nothing between the particles. (Neil, Journal entry 3)

Three months after the instruction, Neil's scientific explanations as to the aspects of the PNM were consistent with his postinstructional responses (see Table 1 for task descriptions):

> *Task 3*: [See Figure 2b.] Particles of gases . . . bounce around . . . (*SciArr_Dist_G*). Particles of liquids are all touching (*SciDist_L*). Particles of solids . . . stay in an organized way (*SciArr_S*).
> *Task 5*: The water molecules are all . . . bumping into the food coloring by moving them even farther around until all of the water appears blue (*SciMove_Uni_L*).

> *Task 7*: [See Figure 2c.] When a gas is cooled, the attraction forces between particles become stronger, and they begin moving slowly . . . (*SciMove_Force_L_G*).
> *Task 8*: Particles of solids have a stronger attraction force to each other. When solids melt, particles of solids begin moving faster (*SciMove_S_L*), so the attraction forces between particles become less powerful, because energy is added to them (*SciForce_S*). Particles of liquids are loosely attracted but still touching each other (*SciForce_Dist_L*).

Comparison of Neil's responses on the pre and postinstruction indicated that he should have experienced major restructuring in his explanatory framework, leading to the development of a stable scientific understanding of the PNM. From the pre to postinstruction, he both extended his explanatory framework by incorporating new conceptions (e.g., the existence of electrostatic forces, the motion of particles of solids) and changed the ones competing with the scientific view (e.g., the arrangement of particles of solids, the spacing between particles of liquids, and the existence of nothing between the particles). He also indicated persistence in his scientific conceptions of the PNM over a 3-month period.

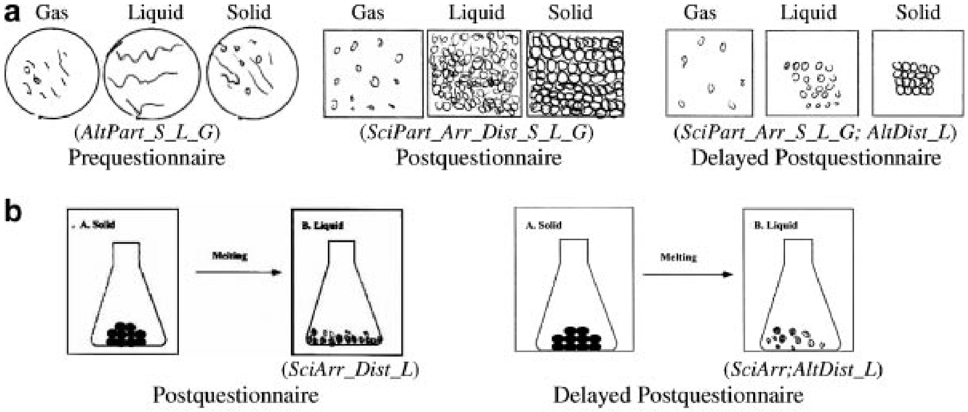
Conceptual Pathway 2: Radical Progress with a Moderate Decay

The conceptual understandings of Beth, Ernie, and Robert advanced from either alternative fragments or alternative with scientific fragments to a full scientific understanding of the PNM from pre to postinstruction. These students' conceptual understandings then moderately decayed over a 3-month period, as their conceptual understandings regressed to scientific with alternative fragments (see Table 3 and Figure 1).

Robert, for example, started the instruction with the type of understanding of alternative fragments, including several nonscientific conceptions in his explanatory framework (see Table 3). Before the instruction, Robert utilized the terms of "molecules" or "particles" in his verbal explanations of different phenomena (see an excerpt at the end of this paragraph), but his pictorial representation of matter on a small scale did not align with the discrete nature of matter in all physical states, including both macroscopic (solid wavy lines) and submicroscopic (little circles) representational features. Thus, the researchers conservatively coded his conception of the discrete nature of matter as alternative. In addition, he did not offer any evidence for understanding the constant motion of particles of solids and liquids, the existence of electrostatic forces among the particles, and the arrangement of and the spacing between particles in all three states of matter. He held an alternative conception about the existence of nothing between the particles (e.g., "There is carbon dioxide between the particles of oxygen gas, because usually oxygen and carbon are mixed together" [*AltEmpty_G*]). Before the instruction, Robert also believed that when half of the gas is released from the closed flask, the remaining gas would stay at the bottom half of the flask (e.g., "The air molecules are fully bouncing around in the compacted area [before releasing]. The pressure goes down and the air molecules stop bouncing around as much [after releasing]. The air sinks to the bottom" [*AltUni_G*]).

The following excerpt from Robert's postinterview transcript demonstrated remarkable progression in his understanding regarding the aspects of the particle theory of matter.

Researcher: How would you explain the dissolving of sugar in water?
Robert: I guess the water breaks sugar down. As it breaks down into molecules, sugar molecules just evenly mixes with the water molecules . . . (*SciMove_Uni_L*).
Researcher: What happens to the particles of a gas, if a gas turns into a liquid?
Robert: [See Figure 3a.] . . . the particles of a gas are not organized . . . they are just kind of sporadically moving around (*SciArr_Move_G*) . . . once they turn into a liquid, they are more organized . . . but . . . still loosely packed together . . . (*SciArr_Dist_L*).
Researcher: How does the behavior of particles change, when a solid becomes a liquid?
Robert: [See Figure 3b.] . . . particles of solids are together and evenly organized, they move together . . . (*SciArr_Dist_Move_S*), and when they melt . . . they are loosely packed, and . . . not as organized either, they move around . . . (*SciArr_Dist_Move_L*).
Researcher: What keeps the particles of solids together?
Robert: The attraction forces. The attraction between the particles of a solid . . . like, a lot more than they would be as a liquid, quite more than (*SciForce_S_L*).
Researcher: You said it is easy to compress gases. Would you please explain why it is to do so?



(*AltPart_S_L_G*) Prequestionnaire

(*SciPart_Arr_Dist_S_L_G*) Postquestionnaire

(*SciPart_Arr_S_L_G; AltDist_L*) Delayed Postquestionnaire

(*SciArr_Dist_L*) Postquestionnaire

(*SciArr;AltDist_L*) Delayed Postquestionnaire

Figure 3. (a) Robert's representation of the three states of matter. (b) Robert's representation of the melting of solids.

Robert: . . . gases have empty space in between the particles . . . Once you compress them, the particles are closing in together, and filling in the gaps . . . (*SciEmpty_G*).

Based on Robert's responses on the delayed postquestionnaire, it appeared that his conceptual understanding of the PNM remained stable for almost all aspects of the PNM, but identification of an alternative conception in his explanatory framework about the spacing among particles of a liquid resulted in classifying his type of conceptual understanding as scientific with alternative fragments. Roberts' explanations 3 months after the instruction follow:

> *Task 3*: [See Figure 3a.] Particles of gases are uneven and scattered around (*SciArr_Dist_G*) . . . Particles of liquids are still closer together but not completely (*AltDist_L*). Particles of solids are stuck together and . . . they move but only vibrating together (*SciArr_Dist_Move_S*).
> *Task 5*: When the food coloring enters the water, it sinks straight to the bottom. After time passes, the food coloring . . . diffuses and spreads out evenly (*SciMove_Uni_L*).
> *Task 8*: [See Figure 3b.] When solids melt, the particles get loosely packed, because the attraction ability of forces between the particles weakens (*SciForce_S*).
> *Task 9*: When gases get compressed, the particles have less space . . . and are packed together. The fact is that there is nothing in between the gas particles (*SciEmpty_G*).

Comparing Robert's pre and postinstructional responses suggests that even if he started the instruction with a limited explanatory framework, comprising either no understanding or nonscientific views about the aspects of the PNM, he then exhibited considerable growth in his conceptual framework by changing, incorporating, and arranging numerous conceptions of the PNM. If Robert's case is interpreted from Vosniadou's (1994) view, it seems that his conceptual framework underwent strong conceptual restructuring with a series of revision and enrichment processes. Robert's alternative conception of the existence of some space between particles of liquids, which led to a moderate decay in his conceptual understanding of the PNM over a 3-month period, might have existed in his explanatory framework before the instruction, but this idea would not have been diagnosed. He likely developed a scientific conception about the spacing among particles of liquids during the instruction, and the status of this particular conception temporarily raised (Hewson & Thorley, 1989). Nevertheless, the conception might not have been well integrated into his conceptual framework at that time. This particular conception probably remained unstable in the framework and was not the primary focus of his chemistry studies over a 3-month period. When he was challenged with the concept of spacing between particles of matter 3 months after the instruction, Robert would have created a response on the spot by drawing upon the most reasonable idea that he perceived as accurate at the time (see Vosniadou & Brewer, 1992).

Conceptual Pathway 3: Moderate Progress and Stable

Four (Sally, Alison, Carey, and Erika) students' initial type of understandings were identified as scientific with alternative fragments, but then these students' type of understandings progressed to a full scientific understanding after the instruction, and they maintained their scientific understandings of the PNM over a 3-month period (see Table 3 and Figure 1). Sally was chosen as a typical case to illustrate the conceptual pathway of moderate progress and stable.

Before the instruction, Sally offered evidence for viewing matter as being made of discrete particles. Although Sally verbally described the spacing among particles of liquids as "closer together" (*AltDist_L*), the spacing among particles of a liquid looked even farther apart in her preinstructional pictorial representation, like the spacing between the particles of a gas (see Figure 4a). Sally also provided no evidence of understanding the electrostatic forces acting between the particles, even if she held solid ideas about the motion of particles, the uniform distribution of particles of liquids and gases, and the existence of a vacuum between particles of matter. Excerpts from Sally's prequestionnaire responses to the various tasks follow:

> *Task 2*: . . . Molecules of a gas get further apart after releasing some of the gas, and . . . because there are not as many air molecules (*SciUni_G*).
> *Task 5*: The water molecules and the food coloring molecules move around and they mix (*SciMove_Uni_L*).
> *Task 7*: It [cooling of a gas] slows down the molecules (*SciMove_L_G*) and makes them get closer together (*SciDns_L*).
> *Task 8*: The particles of solids are moving slow, because they are so close together, they vibrate up against each other (*SciMove_S*). The particles of liquids move slower and spread out (*SciMove_L*) because they do not need to stay so close together (*AltDist_L*).
> *Task 10*: There is nothing between the particles of oxygen, because if there was anything then it would not be oxygen (*SciEmpty_G*).

Excerpts from Sally's postinterview explanations follow:

Researcher: What happens to the particles of a gas, when the gas cools down until it liquefies?
Sally: [See Figure 4a.] . . . particles of a gas are moving very quickly . . . As they are cooled down, they slow down, and they become closer . . . (*SciMove_L_G*).
Researcher: . . . What keeps the particles of a liquid closer together?
Sally: Attraction forces between particles (*SciForce_L*).
Researcher: What would you say about the attraction forces between particles of matter?
Sally: The attraction forces between particles of gases are very little compare to the attraction forces between the particles of liquids (*SciForce_L_G*).

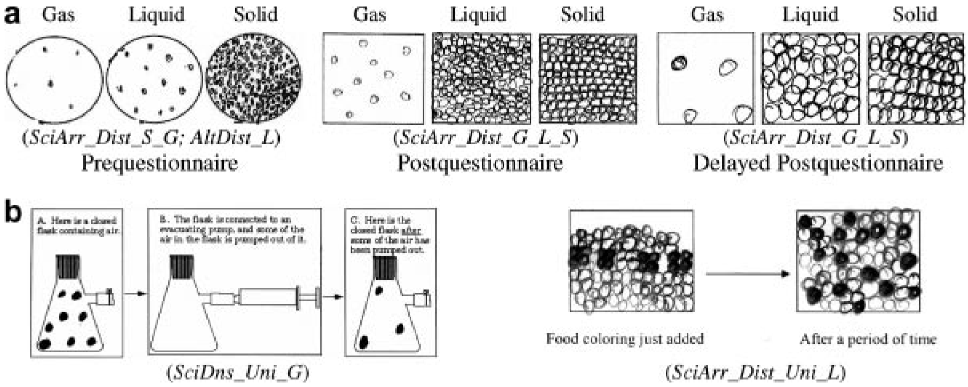


Figure 4. (a) Sally's representation of the three states of matter. (b) Sally's representation of the two tasks on the delayed postquestionnaire.

Researcher:	What happens to the particles of a solid when it turns into a liquid?
Sally:	[See Figure 4a.] Particles of solids are regularly aligned (*SciArr_S*), and they are vibrating back and forth (*SciMove_S*), but as they are heated up, they speed up . . . (*SciMove_L*)
Researcher:	You said that it is easy to compress gases. Why is it easy to compress gases?
Sally:	. . . in between the molecules is just space, there is nothing there, so as you compress the air molecules . . . they can become closer together . . . (*SciEmpty_G*).

The following excerpts and samples of her pictorial representations (see Figure 4a and b) reflect Sally's conceptual understanding of the PNM 3 months after the instruction:

> *Task 5*: [See Figure 4b.] The food coloring . . . spreads out over the top as time goes on the food coloring molecules move around and disperse evenly throughout the water (*SciMove_Uni_L*).
> *Task 7*: Particles slow down and move closer together as the gas cools down (*SciMove_Dist_L_G*).
> *Task 8*: [See Figure 4a.] Particles of solids have a lot of attraction forces to each other (*SciForce_S*). As they melt, the attraction force between the particles becomes less and particles of liquid move quicker. They can slide past each other and are not very attracted as much (*SciMove_Force_L*).
> *Task 10*: There is nothing, there are only oxygen particles in the flask (*SciEmpty_G*).

After the instruction, Sally not only refined, elaborated, and strengthened her explanatory framework by consistently associating the aspects of the particle theory of matter, but she also moderately restructured her conceptual framework and maintained her newly constructed conceptions over a 3-month period. It appears that Sally properly incorporated the new concept of the existence of electrostatic forces into her explanatory framework, because her responses to the task of condensation of gases on the postinterview and to the task of melting on the delayed postquestionnaire indicated that she was able to attribute any change in the attraction ability of electrostatic forces to the change in the motion of particles. Moreover, her preinstructional alternative conception concerning the distances between particles of liquids had shown up neither shortly after nor 3 months after the instruction. Sally should have found the idea as to the existence of similar spacing between the particles of solids and liquids fruitful during the instruction, stimulating the rise in the status of the scientific view.

Conceptual Pathway 4: Moderate Progress with a Full Decay

Only one student (Heather) whose initial conceptual understanding was classified as alternative understanding with scientific fragments engaged in the instruction with a highly unstable explanatory framework consisting of several nonscientific conceptions of the PNM with discrete pieces of scientific conceptions embedded into the existing one (see Table 3 and Figure 1). Her conceptual understanding progressed to the type of understanding of scientific fragments following the instruction. However, Heather's newly constructed conceptions of the PNM did not display persistence over a 3-month period. Her postinstructional type of understanding of the PNM regressed to her preinstructional type of understanding with a full decay.

Based on Heather's verbal explanations on the prequestionnaire, she frequently used the notion of particles or molecules (see an excerpt below), but she should have failed to pictorially utilize the discrete nature of matter to all three physical states. Her pictorial drawings on the prequestionnaire showed matter in solid and gas state with little circles, which usually represent the particles, whereas her representation of matter at the liquid state consisted of little squiggle marks, which is commonly considered as nonscientific submicroscopic representation of matter (see Figure 5a). In fact, this one incidence does not imply that she did not hold the particle ideas at all, but her understanding of discrete nature of matter for liquid state was strictly coded as being alternative due to inconsistencies in her representations of matter. In addition, Heather exhibited alternative conceptions about the arrangement of particles of solids (see Figure 5a) and the distances between particles of liquids on the prequestionnaire [e.g., "particles of solids are very close together, but particles of liquids farther apart (*SciArr_S*; *AltDist_L*)"]. She also provided no evidence of understanding the concepts of the motion of particles of solids, the electrostatic forces acting between particles, and the existence of a vacuum in between the particles of matter. Excerpts from Heather's prequestionnaire responses follow.

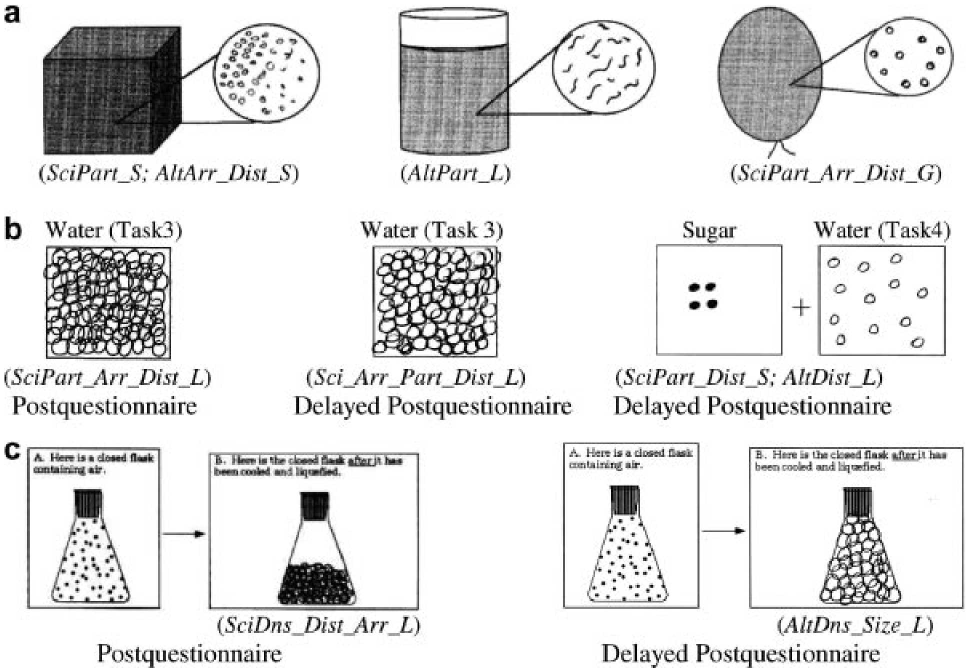


Figure 5. (a) Heather's representation of the three states of matter on the prequestionnaire. (b) Heather's representation of the liquid state. (c) Heather's representation of the condensation of gases.

> *Task 2*: . . . When some air pumped out from the flask, the air in the flask has more room and . . ., the air probably expands because there is more room and less air (*SciUni_G*) . . .
> *Task 4*: The sugar molecules are smaller than the water molecules, therefore, they break down faster and the water is able to absorb the sugar molecules (*AltDiss*).
> *Task 5*: After adding the food coloring, particles of the food coloring expand throughout all the water molecules, which make the water uniformly blue (*SciMove_Uni_L*).
> *Task 6*: The gas seeps into the air and expands throughout the air container (*SciMove_G*).
> *Task 8*: When a solid turns into a liquid, the particles of the solid expand (*AltSize*), because they get warmer and spread apart (*AltDist_L*).

Excerpts from Heather's postquestionnaire responses follow:

> *Task 3*: [See Figure 5b.] Particles of a liquid are very close together and arranged randomly (*SciArr_Arr_L*). Particles of a solid are very close together and are in an orderly arrangement (*SciArr_Dist_S*).
> *Task 5*: When the food coloring is first dropped into the water, it goes straight to the bottom . . . then, the molecules are able to evenly mix in with the water (*SciMove_Uni_L*).
> *Task 7*: [See Figure 5c.] . . . when the gas is present, the particles are far apart and moving rapidly (*SciDist_Move_G*), however, when the gas is cooled . . . the particles come tightly packed together (*SciDist_Dns_L*).
> *Task 8*: Particles of a solid do not move very much, they just vibrate . . .(*SciMove_S*).
> *Task 9*: Particles of a gas are spread out more before compression but when compressed, the "nothing" between the gas particles is gone making the molecules closer together (*SciEmpty_G*).

Heather's postinstruction responses revealed that she developed scientific ideas about almost all aspects of the PNM, particularly the ones with which she had conceptual difficulties before the instruction, but she failed to provide evidence for a concept of the electrostatic forces existing between the particles of solids and liquids.

Heather's newly constructed scientific ideas deteriorated over a 3-month period. Excerpts from Heather's delayed postquestionnaire responses follow:

> *Task 3*: Particles of gases are spaced out . . . (*SciDist_G*). [See Figure 5b.] Particles of liquids are randomly arranged but are very closely packed . . . (*SciArr_Dist_L*). Particles of solids are closely arranged . . . in an orderly pattern (*SciArr_Dist_S*).
> *Task 6*: Particles of air and colored gas move through the valve and the air and gas are intermixed in both containers (*SciMove_Uni_G*).
> *Task 7*: [See Figure 5c.] Particles begin to slow their movement because of the cooling (*SciMove_L_G*) . . . particles of a gas move closer together which then forms a liquid (*SciDns_L*).
> *Task 8*: . . . When melting, the particles start to get warmer and start moving more rapidly because they are being heated (*SciMove_S_L*) . . .
> *Task 9*: Particles of a gas are spread farther apart and they have more space in between the particles so they can be compressed easily (*NoCUofEmpty*).

Note that all the scientific conceptions evidenced in her explanatory framework on the delayed postquestionnaire already existed in her preinstructional explanatory framework (e.g., the motion of liquid and gas particles and the uniform distribution of liquids and gases). Differing from her preinstructional responses, her delayed postquestionnaire explanation of the arrangement of and spacing between particles of all three states of matter were more illustrative. Moreover, on the delayed postquestionnaire, Heather's verbal explanation of the spacing between particles of liquids seemed scientific, but comparison of her pictorial representations of the liquid state in a different task revealed inconsistencies (see Figure 5b). For example, when Heather was explicitly posed a question about the spacing between the particles of liquids (Task 3), her pictorial representation of liquid state aligned with her verbal explanation of the liquid state. Yet, her pictorial representation of the liquid state for the task of dissolving of sugar, where no cue was provided about the spacing of particles, resembled the gas state (see Figure 5b).

In her delayed postquestionnaire response to Task 7, Heather said that, when cooling, "the gas particles move close together which then forms a liquid." This explanation differed from her pictorial representation that depicted a change in size of the gas particles while turning into a liquid (see Figure 5c). Because of these discrepancies in her verbal and pictorial representations on the delayed postquestionnaire, the conceptions of spacing between particles of liquids and the density of the particles in different physical states were coded as being alternative.

Heather offered evidence for holding the concept of the existence of nothing between the particles following the instruction. However, Heather seemed to imply that nothing exists between the particles with the term *space* in her delayed postquestionnaire explanation for Task 10. Yet, because she did not explicitly state that it is empty space, her explanation was coded as no understanding of the existence of a vacuum between the particles. Besides, even if the conception of the motion of particles of solids was evidenced on the postquestionnaire, this particular concept was not observed in her explanatory framework on the delayed postquestionnaire. The concept of the motion of particles of solids likely had been integrated into her explanatory framework during instruction, and perhaps it should have been inert on the postquestionnaire (see Vosniadou, 2003). Because it was not revisited over a 3-month period, this concept should have not survived longer in her conceptual framework.

Heather reflected on the concept of the electrostatic forces that keep the particles of solids and liquids together in her journal entry during the instruction (e.g., "I know that solids are attracted to each other and do not move much, however, when the solids were heated . . . and not be so attracted to one another" [Journal entry 5]). Yet, she probably either was not able to integrate this particular conception into her conceptual framework or had not perceived this idea fruitful for explaining various phenomena. Thus, the concept of electrostatic forces acting between the particles did not exist in her explanatory framework after the instruction.

Conceptual Pathway 5: Slight Progress and Stable

Before the instruction, six (Miles, Keith, Nora, Jenna, Autumn, and Diana) students' conceptual understandings of the PNM were identified to be alternative understanding with scientific fragments. Then, they showed slight (one category) conceptual progression toward a scientific understanding, where their understandings were classified as scientific understanding with alternative fragments (see Table 3 and Figure 1). These six students then maintained their newly developed postinstructional conceptions of the PNM over a 3-month period.

Diana's verbal and pictorial responses at three data collection points are presented here as an exemplary case for the conceptual pathway, "slight progress and stable." Her preinstructional pictorial representations of the three states of matter indicated that she encountered difficulty in perceiving matter as discrete particles for the gas state (see Figure 6a). Diana also held alternative conceptions of the arrangement of and the spacing between particles of matter before the instruction, exhibiting various other alternative conceptions of the PNM in her explanatory framework. Excerpts from Diana's prequestionnaire responses follow.

> *Task 5*: Once you add food coloring into water, the color will fill all the water because the food coloring is heavier than water (*NoCU*).
> *Task 6*: The colored gas will take over the air, because it is heavier than air (*NoCU*).
> *Task 7*: The particles of air become more loose causing them to become a liquid (NoCU).
> *Task 8*: Particles of a solid are closer together, . . . and they do not move a lot (*SciMove_S*). When it melts, the particles loosen and aren't organized and compact (*SciArr_L*; *AltDist_L*). Particles of a liquid move around . . . (*SciMove_L*).
> *Task 10*: There exists carbon dioxide. Whenever oxygen is present carbon dioxide usually is too (*AltEmpty_G*).

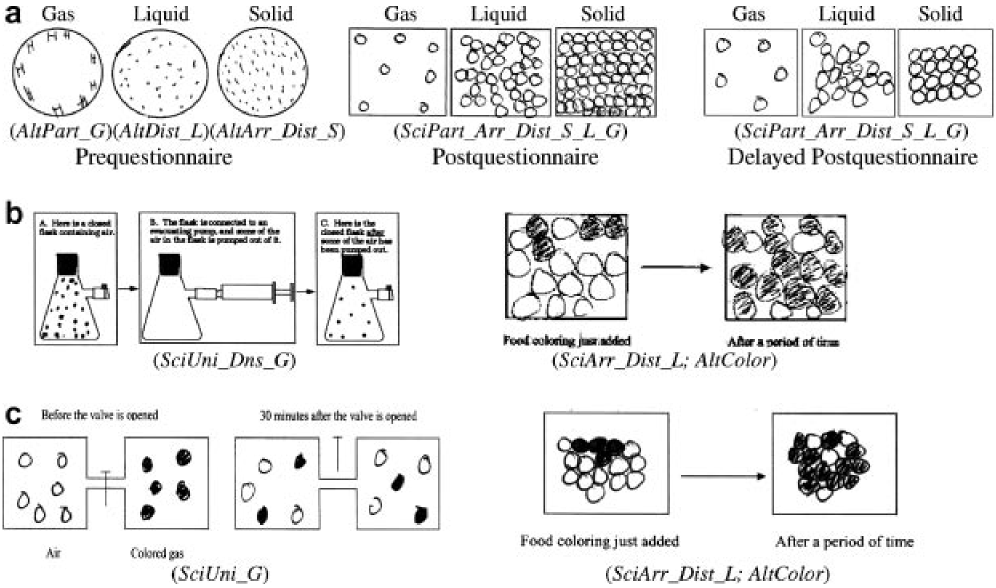


Figure 6. (a) Diana's representation of three states of matter. (b) Diana's representation of the uniform distribution of gases and diffusion of food coloring in water on the postquestionnaire. (c) Diana's representation of uniform distribution of gases and the diffusion of food coloring in water on the delayed postquestionnaire.

Diana's postinterview responses follow:

Researcher: Would you please tell about your pictures for the food coloring task?

Diana: [See Figure 6b.] . . . when they are just added, the particles are at the top, and there is more water particles, and after they sink to the ground and take up the place of the water particles.

Researcher: You had drawn four molecules of food coloring in the first picture on the left, then, there are more than four molecules of food coloring in the second picture on the right. How would you explain that?

Diana: I think the food coloring takes place of the water particles. That is why there are fewer water particles in the second picture (*AltColor*).

Researcher: When a gas cools down, how does the behavior of gas particles change?

Diana: The gases are free and move around faster, when it cools down, the particles begin to slow down (*SciMove_L_G*), and then . . . they get closer together (*SciDns_L*).

Researcher: What keeps the particles closer together?

Diana: I do not know. They just move slower, and hmm . . . (*NoCUofForce*).

Researcher: What happens to the solid particles, when a solid melts?

Diana: The particles of solids are tightly packed and they barely move, they just vibrate (*SciDist_Move_S*), and when they melt, the particles start vibrating faster . . .

Researcher: What is there between particles of a gas?

Diana: Air. Air is everywhere, so between those particles there must be air (*AltEmpty_G*).

The following excerpt is from Diana's delayed postquestionnaire:

> *Task 5*: [See Figure 6c.] . . . As time goes by the food coloring molecules slowly turn the water blue, but there are still some water molecules that are not colored . . . (*AltColor*).
> *Task 6*: [See Figure 6c.] The particles mixed together because air molecules are always moving, so the molecules moved together (*SciMove_Uni_G*).
> *Task 7*: Once it gets liquefied, particles of a gas start to slow down and become less free to move around (*SciMove_L_G*). The particles also do not take over the whole container as the gas did (*SciDns_G_L*).
> *Task 8*: Particles of solids are tightly packed because they are extremely organized and barely move. It almost seems as though they vibrate (*SciArr_Dist_Move_S*). The air molecules between the particles keep the particles together (*AltEmpty*; *NoCUofForce*). When it melts, the particles of a liquid . . . are not tightly packed anymore . . . (*SciDist_L*).

Diana entered the instruction with mostly nonscientific views of the PNM (e.g., the discrete nature of the gas state, the spacing and the arrangement of particles, and the existence of a vacuum among particles), and she failed to provide evidence of understanding the electrostatic forces acting between particles. Her postinstructional responses revealed that she developed a scientific view of the discrete nature of matter equally across the three physical states, and the spacing and arrangement of particles in all three states of matter. She also provided clear explanations about the motion of particles and the uniform distribution of gases.

Diana's vague explanation concerning the coloring of particles was interpreted as alternative conception before the instruction (see her response to Task 5). Yet, her distinctive alternative conception about the coloring of particles became evident with the evidence she offered on the post and delayed postquestionnaire. Those evidences indicated that perhaps she was not aware of the fact that any macroscopically observed properties of a substance (e.g., color, hotness or hardness) cannot be associated with the individual particles, but a substance needs to be conceived of as collective properties of particles. Diana apparently encountered difficulties in making transitions between macroscopic and submicroscopic views of matter (Buck et al., 2001; Johnson, 1998). According to Talanquer (2009), viewing the particles as having the properties of macroscopic sample of a substance is a strong and pervasive presupposition that constrain students' understanding of the other aspects of the PNM.

Drawing upon Vosniadou's (1994) perspective, Diana's alternative conception of the existence of some substance such as air in between the particles of matter should have been constrained by a presupposition in her framework theory (e.g., there is no void, and air fills up all empty spaces; Talanquer, 2009). Thus, despite the instruction, she persisted in this specific alternative conception. An excerpt from her journal entry supported the claim that she may have never believed in the existence of nothing between the particles even after the class discussions on this concept (e.g., "I think the water particles went in between the alcohol particles and took the place of air particles in between the alcohol particles" [Journal entry 3]).

Moreover, the concept of electrostatic forces acting between the particles was never identified in Diana's explanatory framework across the three data collection points. An excerpt from her journal entry, which she completed following the evaporation of liquids activity, where students had direct experience and class discussion on that phenomenon, provided evidence as to why she was not able to integrate this particular conception in her explanatory framework:

> I thought that when observing the water and alcohol, that the water would evaporate first. I did not understand why the alcohol went first. Now I know that particles are farther apart in gases, and alcohol evaporates faster than water [Journal entry 6].

Note that she had not referred to the change in the attraction ability of electrostatic forces between the particles of liquids when liquids turn into a gas. Diana must have found this conception challenging and was not able to construct stable scientific conception during the instruction; thus, she may have then preferred not to use this particular idea in her explanation.

Conceptual Pathway 6: Stable with Slight Progress

Sean's type of understanding of the PNM indicated no progression from pre to postinstruction, but his responses to the delayed postquestionnaire exhibited slight progress (see Table 3 and Figure 1). Even though Sean held a scientific understanding of the discrete and dynamic nature of matter before the instruction, he held multiple nonscientific views about the arrangement of and spacing between particles of solids (see Figure 7a) and the electrostatic forces existing between particles. The following are excerpts from Sean's prequestionnaire:

> *Task 2*: The air molecules inside the flask are tightly packed. Once air is pumped out, the other half of the air . . . have more space . . . (*SciUni_G*).
> *Task 3*: [See Figure 7a.] . . . Particles of a liquid are compacted (*SciDist_L*) to make the water appear. The particles are moving very slow when it's a solid (*SciMove_S*).
> *Task 6*: The air and the colored gas are going to mix and make a chemical reaction (*AltForce*).
> *Task 7*: When cooling the gas until it liquefies, the particles are going to be moving very slowly . . . (*SciMove_G_L*).

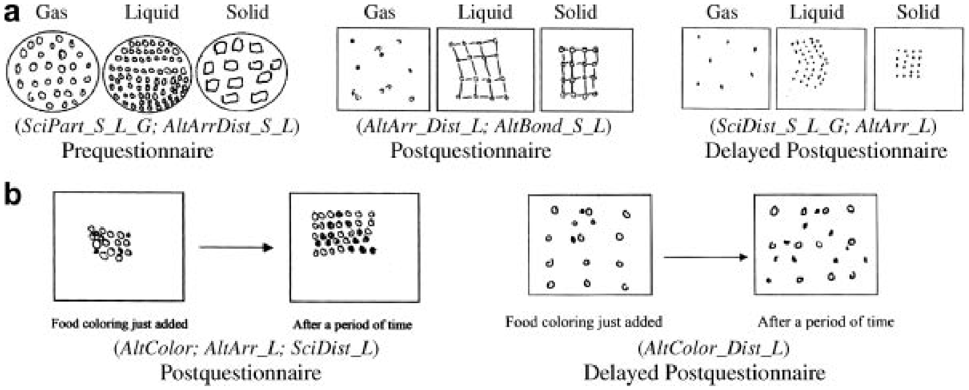


Figure 7. (a) Sean's representation of three states of matter. (b) Sean's representation of diffusion of food coloring.

> *Task 8*: The solid is hard and in order to stay hard, the particles must be packed tightly (*SciDist_S*). Chemical bonds keep the solid particles together . . . (*AltForce*).
> *Task 10*: There is space in between the molecules, because there isn't all the air that can fit in there (*NoCUofEmpty*).

Note that his understanding of the existence of nothing between particles was conservatively coded as no conceptual understanding in all three data collection points. His use of the term *space* may appear to imply the existence of empty space between the particles, but from Sean's perspective, the space might have been filled with some substance.

Excerpts from Sean's postinstruction responses follow:

> *Task 3*: [See Figure 7a.] . . . The solid is sitting there vibrating . . . (*SciMove_S*).
> *Task 5*: [See Figure 7b.] . . . that the food coloring had time to spread out in the water. As more time passes along the food coloring will cover the whole water up (*SciMove_Uni_L*).
> *Task 6*: Once the valve is opened, both air and the colored gas mix (*SciMove_G*). Now, both particles are on both sides of the boxes (*SciUni_G*).
> *Task 8*: A solid is tightly packed because of chemical bonds (*AltForce*). When it melts, the solid isn't tightly packed anymore because it is turning into a liquid. Liquid particles have a little more room then solids (*AltDist_L*).
> *Task 10*: There is space between the oxygen, because there are no particles in between the oxygen particles (*NoCUofEmpty*).

The following are excerpts from Sean's delayed postquestionnaire responses:

> *Task 3*: [See Figure 7a.] The gas vapor does not have many particles in there . . . particles of a liquid are compacted . . . (*SciDist_L*). Particles of solids are tightly packed because a solid has a definite shape and they are just vibrating (*SciDist_Move_S*).
> *Task 5*: [See Figure 7b.] After a while the food coloring starts to spread down the water covering more space (*SciMove_L*).
> *Task 6*: When the valve is opened, the colored gas and air is mixed (*SciMove_Uni_G*).
> *Task 7*: Once the flask has been cooled and liquefied, all the particles have gone toward the bottom (*SciDns_L*).
> *Task 10*: There is space between particles of oxygen (*NoCUEmpty*).

Categorization of the codes emerging from Sean's responses in all data collection points offered evidence that he considered matter as being made of particles and as in constant motion in three physical states. However, his pre and postinstructional verbal explanations of the arrangement of and the distances between particles of solids and liquids were unclear and not in line with his pictorial particulate representations of the solid and liquid state. Consistent with Taber's (2000) claim regarding the coexistence of multiple conceptions, Sean's pre and postinstructional verbal and pictorial representations also indicated alterations with respect to the context of tasks and the cues provided in the description of the tasks (see Figure 7a and b), holding both scientific and nonscientific views about the aspects of the particle theory of matter in his conceptual framework. A careful examination of his pre and postinstruction responses displayed no progress in his explanatory framework in the form of either addition of a new conception or elimination of or change in his alternative conceptions.

Sean's perception of physical changes as being chemical phenomena for different tasks on the prequestionnaire may have indicated that Sean perhaps encountered difficulty in understanding the electrostatic interactions between the particles (Johnson, 1998; Talanquer, 2009). However, his preinstructional pictorial representation of the solid and liquid state did not display stick-type bonds between the particles (see Figure 7a). Despite the instruction, Sean failed recognizing the electrostatic interactions in physical and chemical changes. It seems likely that in-class discussions on the existence of electrostatic forces between particles in explaining the phase changes may have resulted in creation of an instruction-induced alternative conception (synthetic model of matter; see Vosniadou et al., 2001), which appeared in his representations of solids and liquids as being solid lines between the particles of solids and liquids following the instruction (see Figure 7a). In addition, note that the ball-and-stick models are frequently used in textbooks to represent the bonds within a molecule (Griffiths & Preston, 1992). During the instruction, Sean may have erroneously associated the existence of electrostatic forces between particles with the textbook misrepresentations of bonds. This interpretation may have led to the generation of a mental model that solids and liquids were represented as being stick-type bonds in between the particles.

Interestingly, Sean seemed to give up his alternative conceptions of associating physical phenomenon with chemical change and the stick-type bonds between the particles of solids and liquids over a 3-month period (see Figure 7a). Whereas, the three already existing alternative conceptions (e.g., coloring of particles and the arrangement of and spacing between particles of liquids) recurred in his responses on the delayed postquestionnaire, he held fewer alternative conceptions. Thus, his understanding was categorized as scientific with alternative fragments 3 months after the instruction.

Discussion

The current study mainly explored the patterns of Grade 11 introductory chemistry students' conceptual pathways of the PNM from pre to postinstruction to 3 months after the multirepresentational instruction. Findings of the study suggested positive conceptual progression in 18 of the 19 students' conceptual understanding of the PNM, varying from radical to slight change (conceptual pathways of 1–5). The majority of the students (13 of the 19) maintained their postinstructional conceptual understandings over a 3-month period (conceptual pathways of 1, 3, 5, and 6), whereas, 5 of the 19 students exhibited a diverse degree of decay in their understandings of the PNM (conceptual pathways of 2 and 4). The findings of the study were consistent with the previous research as to the patterns of progression from *radical* to *no change* as an immediate learning outcome (Malandrakis, 2006) and then either durability or regression in students' understandings (Trundle et al., 2007; Tytler, 1998a).

Examining the role of multirepresentational instruction on student learning from the standpoint of the students and the teacher based on their self-reported perceptions would have provided valuable information about the efficacy of the instruction, but this aspect was not the focus of the study. Additionally, the first author observed all instruction and took field notes on the fidelity of the implementation. Also, the first author's interaction with some participants (e.g., Jenna) toward the end of the interview might give some sense of how students perceived the instruction. Jenna found the instruction engaging and different from her regular instruction, and she said, "We talked about the particles a lot, drawing particle models and seeing animations helped me learn better about the particles." In addition, 1 day, the teacher herself spontaneously told the first author that "Visual models make more sense to students. I began to use the same materials (static models and animations) with my Grade 9 students" for teaching the behavior of matter at three physical states.

The theoretically developed learning progressions by Smith et al. (2006) and Stevens et al. (in press) for the topic of nature of matter were the latest efforts and large in scope in terms of including a broad period of time (Grade K-8 and Grades 7–14, respectively). The current study differed from these two studies by providing more fine-grained depictions of Grade 11 students' conceptual pathways of the PNM in a multirepresentational instruction context over a limited period of time. However, the findings of the study offered empirical evidence for commonly accepted feature of conceptual pathways; that is, students are likely to pursue multiple conceptual pathways as to interaction between their prior knowledge and the instruction they encounter (Lehrer & Schauble, 2009; NRC, 2007; Rea-Ramirez, 2008).

Steedle and Shavelson (2009) suggested that before collecting and analyzing data "it is not feasible to develop learning progressions that can adequately describe all students' understanding" (p. 713). Concerning this issue, in the present study, the types of conceptual understanding categories (excluding scientific understanding) on the conceptual pathway continuum were shaped by available data to sufficiently portray the participants' type of conceptual understandings of the PNM (see Table 3). Thus, it is important to recognize the tentative nature of the criteria established for the types of conceptual understandings of the PNM. The labels of conceptual understanding categories and their criteria may need to be further modified with respect to additional data or redefined with very different group of students to represent the development of students' understanding of the PNM.

Comparing the learning outcomes of the present study to similar studies would have some limitations due to such dissimilarities as targeted grade level, established criteria for a scientific understanding, and the tasks used for assessment. For example, Johnson (1998) expected Grade 9 students to develop the idea that particles are the substance and its properties reflect collective behavior of particles. Johnson found that about 44% of Grade 9 students held a scientific model of the PNM (Model C) after completion of the instruction. In addition, Snir et al. (2003) sought explanation of three phenomena (e.g., mixing of water and alcohol) for a scientific understanding. Snir et al. reported that about 40% of Grade 7 students provided scientific responses for all three of the given phenomena immediately after instruction. Moreover, Margel et al. (2008) examined the development of the submicroscopic structure of matter for different substances among junior high school students (Grades 7–9). In Margel et al.'s study, 86% of the participants reached the particle model of matter. Thus, the participants of the current study might be viewed intellectually more mature compared to the participants of the similar studies. However, the scientific understanding criteria for the participants of the study is much more demanding in comparison to other studies such that the students needed to consistently utilize eight aspects of the particle theory of matter for three states of matter while verbally and pictorially expressing their understandings of the 10 phenomena (see Table 3). In this context, it could be cautiously argued that more students in this study (63%) developed a full scientific understanding of the particle theory of matter. If the participants' (Grade 11 students) conceptions about the nature of matter had been assessed by using the criteria established by Margel et al. (2008) (i.e., viewing the matter as particulate), all of the participants in the current study (100%) would have been categorized as having developed a particulate conception of matter for all three states of matter following the instruction, and all of them would have maintained those conceptions over a period of time.

Seven students (Neil, Norris, Ted, Dan, Beth, Ernie, and Robert) in the current study experienced radical progress in their conceptual understandings of the PNM from before to after instruction (conceptual pathways 1 and 2), and 4 of these 7 students (Dan, Beth, Ernie, and Robert) regressed to either scientific fragments or scientific with alternative fragments, exhibiting a slight or moderate decay over a 3-month period (see Figure 1). Indeed, the lack of a full decay among these students' understandings of the PNM was an encouraging outcome in terms of the effectiveness of the multirepresentational instruction. As Mayer (2001) pointed out, multirepresentational instruction fosters the evolution of deeper understandings, given that students have an opportunity to fully utilize their cognitive capability for information processing in multiple modes (verbal and pictorial) with the contribution of multiple sensory channels (hearing and vision). In this context, being able to establish meaningful connections between MRs of the same information appears to be essential in terms of making sense of each unique piece of information associated with each mode of representation (verbal and pictorial) (Ainsworth, 1999; Mayer, 2001). As recognized in the short-term learning outcomes of these seven students, the instruction possibly facilitated the construction of their scientific understandings of the PNM. However, attaining radical progress toward a scientific understanding requires highly sophisticated structuring and restructuring in one's explanatory framework (Vosniadou, 1994, 2003). Thus, some scientific conceptions, particularly the ones competing with the alternative conceptions constrained by particular presuppositions, may have weakly integrated into the conceptual framework of four of the seven students who experienced some degree of decay, and the newly constructed scientific conceptions, consequently, had not survived longer periods of time in these four students' explanatory framework.

Tytler (1998b) justified the reappearance of alternative conceptions or occurrence of decay in scientific conceptions months after instruction, with the lack of time to reflect on the undigested ideas that serve as cues for more advanced explanations. In the present study, scientific understandings of four of the seven students (Dan, Beth, Ernie, and Robert) who experienced radical progress and then some degree of conceptual decay may have been sustained with ongoing assistance and reflection. Aspects of the PNM have explanatory power to account for a range of natural phenomena (Pozo & Gómez-Crespo, 2005). If these students had been confronted with the newly constructed scientific conceptions of the PNM while studying other topics in chemistry, they might have been able to transfer what they learned in the PNM unit to the topic at hand, which may have positively impacted the persistence of these students' scientific conceptions of the PNM over longer periods of time (Georghiades, 2000).

Five students (Sally, Alison, Carey, Erika, and Heather) showed evidence of moderate progress toward a scientific understanding (conceptual pathways 3 and 4), and four of these five students' scientific understandings of the PNM remained stable over a 3-month period (see Figure 1). However, Heather's postinstructional conceptual understanding regressed to her initial understanding with a full decay. In fact, four of the five students (Sally, Alison, Carey, and Erika) already possessed a well-established explanatory framework before they were involved in the instruction (see Figure 1). A close examination of the four students' preinstructional conceptions revealed that they all held two alternative conceptions, and one of which was the most robust and frequently diagnosed one about the spacing between the particles of liquids (Johnson, 1998). All four of the students offered no evidence of understanding of the conceptually demanding concept of the existence of electrostatic forces between the particles before instruction (Adadan et al., 2009; Johnson, 1998; Liu & Lesniak, 2005). Perhaps, this finding leads to the inference that the fewer alternative conceptions students held, the higher the possibility of changing the nonscientific conceptions to a scientific understanding during the instruction. This finding also overlaps with the MRs literature, where Bodemer and Faust (2006) claimed that students with high prior knowledge receive the largest benefit from the pedagogy of multirepresentational instruction. In addition, these four students (Sally, Alison, Carey, and Erika) may have had the potential to metacognitively control their own conceptions. Their ability to monitor their own conceptions and to reflect on their own learning may have helped them make meaningful connections among the aspects of the particle theory of matter, as well as giving rise to the recognition of the incompatibility between their scientific and nonscientific conceptions. Thus, these four students probably became dissatisfied with their existing nonscientific conceptions, which may have facilitated the achievement of stable conceptual change in their conceptual framework (Hewson, 1981).

Six students (Miles, Keith, Nora, Jenna, Autumn, and Diana) who displayed slight progress from pre to postinstruction were likely to maintain their scientific conceptions of the PNM over a 3-month period (conceptual pathway 5; see Figure 1). All of these students' conceptions of the PNM appeared to be enriched as their explanatory framework gradually restructured (as in Tytler, 1998a; Vosniadou, 1994). Before instruction, all six students held either four or five alternative conceptions about various aspects of the PNM. Even though these six students were able to change a few of their alternative conceptions to a scientific understanding, the alternative conceptions that were robust and resistant to change continued to exist in their explanatory framework along with the scientific views of the PNM after the instruction. Among these six students, an alternative conception of perceiving the relative spacing between liquid particles as intermediate compared to the spacing between the particles of solids and gases was frequently diagnosed after the instruction. In fact, the classroom activity of compression of solids, liquids, and gases was particularly designed to challenge students' alternative conception concerning the spacing between particles of liquids. During the instruction, students both had firsthand experience with concrete materials and interacted with visual models. They also had class discussions on the notion of spacing between particles in three states of matter. These students' failure to develop the scientific view about this particular conception despite instruction may have been due to a presupposition (e.g., solid particles are packed in together and almost do not move; when a solid turns into a liquid, particles gain mobility and move somewhat farther apart) that interfered with the scientific view of the spacing of liquid particles (Johnson, 1998). In addition, even though the particle models of matter in three physical states was used as a reference model in all class periods during the instruction, these six students might have relied on the frequent pictorial misrepresentation of the liquid state in the science textbooks that they encountered in the previous years of schooling (see Adbo & Taber, 2009; Harrison & Treagust, 2002). In addition to the possible barriers (presuppositions and misrepresentations) in developing scientific conceptions about the PNM, these six students may not have had strong spontaneous metacognitive skills to manipulate their inconsistent conceptions concerning the spacing between the particles (Buck et al., 2001).

Students' understanding needs to be assessed in multiple contexts to obtain information about coherence and stability of their knowledge (Jimenez Gomez et al., 2006; Steedle & Shavelson, 2009). However, participants' responses to different tasks seemed to be influenced by the context. Participants' inconsistent responses to the tasks with the same underlying principle of the particle theory of matter certainly created a challenge in characterizing their conception of the specific aspect of the particle theory of matter. While dealing with such challenges, the researchers made strict decisions for certain issues and employed them across all cases. In the findings section, the researchers' decisions on certain issues were discussed. The issue of observing inconsistent responses across different tasks for the same student may also be encountered in coding and analysis of students' conceptual progression of the other topics. In addition, the challenge experienced with interpreting students' drawings should be recognized. In this study, to minimize the misinterpretations, students' drawings were compared to their written explanations to make sense of what they intended to represent. In the interviews, students were specifically asked to explain what their drawings for each task show or what they tried to communicate through their drawings (see interview with Diana above).

Implications

Findings of the study suggest potentially important implications for the teaching and learning of science, in particular, the particle theory of matter. First, the teaching approaches used for the multirepresentational instruction can be considered for other similar classrooms to promote conceptual change/learning progression among students. Accordingly, teachers should consider integrating visual tools such as animated or static particulate representations in their teaching practices. Furthermore, teachers should allow students to represent their understandings not only verbally but pictorially (drawings) when appropriate. As mentioned by Van Meter et al. (2006), student-generated drawings provide access to the students' mental models of the phenomena, as well as engage students in integration processes across verbal and pictorial representations, eventually leading to the development of more consistent scientific conceptions.

Second, in the design of the multirepresentational instruction, as suggested by learning progressions research, the identified learning goals were sequenced from less to more sophisticated concepts in a connected fashion. Sequencing of learning goals is critical for teachers to see the overall picture of the topic and plan for the instruction. Moreover, findings of the study indicated that students frequently develop inconsistent (context-dependent) conceptions of the PNM with respect to the nature of task. Thus, teachers should finely blend multiple methods and activities across various contexts to prevent the construction of inconsistent conceptions of the PNM. During the instruction, teachers should ensure that every student attain the desired type of understandings. In this respect, formative assessment appears to be quite essential, particularly in the individual student level. In the current study, the teacher had access to rich information regarding student learning by collecting activity sheets and journal entries. Although students' common conceptual issues of the PNM were addressed in the classroom during the instruction, individual students were not given feedback regarding their learning progression. Therefore, teachers should give feedback to individual students concerning their specific conceptual difficulties, because informing students about their learning progress could allow them to participate more fully in their instruction, as well as enhancing their opportunities for self-regulated learning.

Third, science teachers should be aware of the possible presuppositions students may hold about the aspects of the particle theory of matter, each of which might be an obstacle to both learning the aspects of the particle theory of matter and other topics in chemistry. Respectively, teachers should diagnose the specific alternative conceptions each student holds before the instruction. Findings of the study showed that individual students' initial understandings of the PNM differ from one another in terms of a degree of structure and the number and nature of alternative conceptions so that each student made different extent of progress with respect to their initial conceptual framework. Thus, it appears that students with numerous alternative conceptions and a loose conceptual structure may require particular attention. To ensure that students have properly integrated the scientific conceptions into their conceptual frameworks; teachers should be very explicit about how the new conception is linked to the previous ideas and frequently reinforce these links as appropriate (Taber, 2008).

Inferring from the findings of the study and relying on the past literature (Buck et al., 2001; Hennessey, 2003; Vosniadou, 2003), it seems evident that without explicit metacognitive reflection, promoting stable radical changes in students' conceptual framework is difficult. However, the multirepresentational instruction did not explicitly teach or emphasize the development of metacognitive strategies. Modification of the current multirepresentational instruction by integrating explicit teaching of metacognitive strategies and offering more opportunities for student metacognitive reflection might further promote construction of students' scientific understandings of the PNM.

Earlier research reported a significant correlation between students' conceptions of models and their conceptual understandings of the PNM (Liu, 2006). Because the multirepresentational instruction did not overtly address the purpose and nature of models in science (Grosslight et al., 1991), we are not able to claim any relation between students' understanding of models and their type of conceptual understandings of the PNM. However, providing students with learning environments that encourage discussions on the role of models in the context of scientific inquiry may help them develop proper understandings of the models and modeling as students develop the scientific views of the PNM.

Suggestions for Further Research

The findings of this study shed light on how the instructional pedagogy of the multirepresentational instruction contributes to the development and durability of students' scientific understandings of the aspects of the PNM. The current study was one of the few studies (e.g., Tasker & Dalton, 2006) that employed a mixed set of multirepresentational approaches with Grade 11 students, aiming to promote scientific understandings of the key aspects of the particle theory of matter. Future research should examine how the various instructions foster students' conceptual progression of the PNM in different grade levels.

In addition, conceptual change not only involves cognitive processes but also is stimulated by a range of affective dimensions such as student interest, motivation, and beliefs. Treagust and Duit (2008) claimed that affective dimension "play(s) a significant role in supporting conceptual change on the level of science content knowledge" (p. 300). This study did not inquire about how the instruction impacts students' interest or motivation to learn science, more specifically chemistry. Further research should simultaneously explore the contribution of the instruction to the improvement of affective dimensions in science learning and the construction of the scientific understandings. Such research may provide a more complete portrayal of students' conceptual learning with multidimensional evidence from cognitive and affective domains of student science learning (Treagust & Duit, 2008).

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Appendix A

A Sample of Questionnaire Task

Question 5. **Read the following story, then, answer the question.**

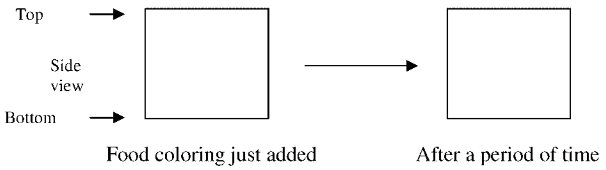
A clear plastic cup is half filled with water. The cup is set on a table where it will not be moved. Then, a few drops of blue food coloring are carefully added to it. After a period of time it is observed that the water is uniformly colored blue.

Twelve molecules of liquid water are placed in Box #1; **four** molecules of food coloring are added to them.

Use **solid** circles to represent food coloring molecules and **open** circles to represent water molecules in the side view of the boxes below. Like this:

● Food coloring molecules
○ Water molecules

In **Box #1**, draw the system when the **4 (four)** food coloring molecules are just added to the **12 (twelve)** water molecules.
In **Box #2** draw the system after a period of time.



Explain your drawings by discussing how the food coloring molecules get from their positions in Box #1 to their positions in Box #2. **The explanation is as important as your drawings.**

Note: Due to the space limitations, the lines provided for answers to the questions were deleted.